CONFERENCE PROCEEDINGS Vol. 1

The Third Gulf

Water

Conference

Muscat, Sultanate of Oman
29 Shawwal - 4 Dhol Qada 1417
8-13 March, 1997

Towards Efficient Utilization of Water Resources in the Gulf

Water Resources Planning and Management
Groundwater Resources
Surface Water and Artificial Recharge Experience

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The Third Gulf Water Conference
Towards Efficient Utilization of Water Resources in the Gulf
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Conference Proceedings

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Edited by

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The Third Gulf Water Conference
Towards Efficient Utilization of Water Resources in the Gulf
Sultanate of Oman, 8-13 March, 1997

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Preface

Within the past decade, a considerable research and experiences have been developed and published on water resources assessment and development, water supply augmentation and maximization, and water facilities management in the Arabian Gulf countries. However, very little research was directed towards demand management, conservation, and efficient utilization of water in the different water consuming sectors. Thus the theme of the conference "Towards Efficient Utilization of Water Resources in the Gulf" was chosen to emphasize the role of conservation and demand management as an important and integral part in water resources management in the Arabian Gulf Countries.

As at the previous WSTA conferences (the first was held in Dubai, 1992, and the second was held in Bahrain, 1994), 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 two previous conferences.

The objectives of the convening conference are: 1) Assessment of natural water resources and alternative sources in the GCC Countries; 2) Review methods of conservation and efficient utilization of water in different sectors, with emphasize on the agricultural and municipal sectors; 3) Review and exchange of local experiences in the field of water resources and sources planning and management; and 4) Review the latest research and advances in the assessment, development, and management of water resources.

The Third Gulf Water Conference is held under the patronage of His Highness Sayyid Haitham Bin Tariq Al Said, and is organized by the Water Science and Technology Association (WSTA) in cooperation with Sultan Qaboos University and the Secretariat General of the Cooperation Council (GCC) for the Arab States of the Gulf. The Conference is sponsored by the Ministry of Electricity and Water, Ministry of Agriculture and Fisheries, Ministry of Water Resources, Ministry of Regional Municipalities and Environment, Ministry of Commerce and Industry, and Muscat Municipality from the Sultanate of Oman, and the Arabian Gulf University (Bahrain), Ministry of Electricity and Water (State of Bahrain), Bahrain Center for Studies and Research, UNESCO Cairo Office (ROSTAS), UN-ESCWA (Jordan), International Desalination Association (IDA), and European Desalination Society.

This conference proceedings contains 84 papers assembled into 4 volumes, one volume in Arabic and the other three in English. The Arabic Volume contains Fourteen papers with most of them having English Summaries, in addition to the organizers speeches. The conference papers were selected by the Conference Scientific Committee from over 110 abstracts received from the call of papers. Many of these were modified to meet the standards of the Scientific Committee review. Conference sessions will be held on topics: Water Resources Planning and Management, Groundwater Resources, Water Desalination, Wastewater Treatment and Reuse, Surface Water and Artificial Recharge Experiences, Water Use in Agriculture and Irrigation Efficiency, Municipal Water Supply Systems, Environmental Protection and Public Awareness and Participation, and Domestic Water Quality.

Six papers are invited by the conference organizers. These are from the Secretariat General of the Cooperation Council (GCC) for the Arab States of the Gulf, Ministry of Water Resources, Ministry of Agriculture & Fisheries, Ministry of Electricity & Water, Ministry of Regional Municipalities & Environment, and Muscat Municipality from the Sultanate of Oman. In addition, Eight renowned international and GCC scientists were invited to give scientific presentations in respective technical sessions, and were supported by the WSTA, UNESCO (Cairo Office), and UNESCWA (Jordan).

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.

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, 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. We sincerely hope that this conference will be both enjoyable and rewarding for you.

Dr. Waleed K. Al-Zubari
Head, Conference Scientific Committee
Desert and Arid Zones Sciences Program
Arabian Gulf University, Bahrain

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Waleed K. Al-Zubari

TOWARDS THE ESTABLISHMENT OF A TOTAL WATER CYCLE MANAGEMENT AND RE-USE PROGRAM IN THE GCC COUNTRIES

Waleed K. Al-Zubari
Arabian Gulf University, PO Box 26671
Manama, Bahrain

ABSTRACT

Water is rather scarce in the GCC countries. Therefore, every drop of water must be carefully used in an economically feasible manner so that no higher quality water should be used for a purpose that can tolerate a lower quality. As a substitute for freshwater in agriculture and industry, treated wastewater has an important role to play in the GCC countries' water resources management. The present gap between water demands and available water resources have led these countries to consider domestic wastewater as an integral part of their water resources. At present, GCC countries recycle no more than 35% of their total treated wastewater, which contributes 2.2% of their total water supply, being used mainly in landscaping, fodder crop irrigation, and some industrial uses. However, major plans for water recycling exist in most of these countries. The main handicaps for reuse expansion are both social (psychological repugnance and religion) and technical (microbiological pollutants, potential heavy metals accumulation in irrigated soil, and industrial waste mixing). If only 50% of domestic water supplies are treated and recycled in agriculture, recycled waters have the potential to meet more than 11% of the GCC countries total water demands, could satisfy more than 14% of their agricultural sector demands, and could reduce fossil groundwater withdrawal by more than 15% by the year 2020.

Keywords: GCC Countries, Water Resources Management, Wastewater Reuse, Wastewater Reuse Constraints, Wastewater Reuse Strategy.

INTRODUCTION

With water becoming an increasingly scarce commodity in the GCC countries, it has now a big potential of becoming a limiting factor for agricultural, and even for industrial development. The greatest challenge the GCC countries are facing is the provision of fresh water supply to meet the domestic, agricultural and industrial sectors demands. With groundwater resources over-exploitation and desalination plants limited capacity, planners are continuously searching for additional sources of water which can be used economically and effectively to promote further development. In these countries treated wastewater is now considered as a new non-conventional source of water that can be used to supplement their total water resources, which consist mainly of groundwater and desalinated water. Beginning from the early 1980s, there has been a growing increase in the use of these waters especially in irrigation and landscaping. This came as a result of the availability of relatively large volumes of treated waters due to the completion of urban wastewater treatment facilities and the expansion of sewage networks in most of the GCC major cities, and, due to environmental considerations, these waters have been treated completely or partially regardless of their utilization. As a substitute to the limited fresh water in the GCC countries, treated wastewater has the potential to play an important role in water resources management and lessen the present and long-term demand vs. supply imbalance.

This paper presents the present recycled volumes and recycling approaches in the GCC countries, anticipated future reused volumes, major benefits of recycling, main handicaps of recycling, and a recommended recycling strategy for a better and full utilization of treated wastewater.

GCC PRESENT WATER RESOURCES/SOURCES

The six GCC countries have an arid to extremely arid climatic conditions. They are characterized by irregular, scanty rainfall (<100 mm/y), and high evaporation rates (>3000 mm/y), leading to large deficits in their water budget, and therefore, creating an impossible conditions for a perennial surface water system to exist. Fresh water demands in these countries have been met by groundwater abstraction (traditionally), desalination plants (introduced in the mid-1960s), and recycling treated wastewater (introduced in the early 1980s). The following is a brief discussion of each.

Groundwater Resources

Groundwater resources in the GCC countries are vast and extend almost over all the six countries (e.g. Dammam, Neogene, Umm Er Radhuma aquifers).

However, most of the water contained in these aquifers are considered to be fossil waters, developed during the rainy Pleistocene and Pliocene geologic ages. Although the strategic storage of the main groundwater units in the Arabian Peninsula is estimated to be around 40 MMm^3 (Ismail, 1995), renewable groundwater resources are very limited, with an estimated annual groundwater recharge for all the aquifers in the GCC countries at about 3,257 Mm^3/y (Table I). Comparison between the annual groundwater recharge and groundwater abstraction rates, which are used mainly to fulfill the agricultural sector demands, indicates that most of the countries' groundwater resources are over-drafted and are depleting. In other words, water abstracted is being taken from groundwater storage, with no significant recharge for the amounts withdrawn. This has resulted in a continuous decline in groundwater levels and quality deterioration in most of the countries due to seawater and connate waters encroachment (Al-Mogren, 1995).

Desalination Plants

In order to meet both the qualitative and quantitative requirements for drinking water standards, domestic water supplies in the GCC countries rely mainly on desalination plants produced water, which are used either directly or blended with groundwater. At present the total capacity of desalination plants in the GCC countries is about 1,852 Mm^3/y (Table II), with a total produced water of about 1,548 Mm^3 in 1992. In order to meet domestic water demands, which is a function of population and urbanization growth, the GCC countries are going ahead with desalination plants construction, despite their relatively enormous costs, which range between 1-1.5 US$/$m^3$ (Bushnak, 1995). It is expected that the total desalination capacity of the GCC countries will be more than 2,200 Mm^3/y by the year 2000 (Al-Sofi and Al-Sayed, 1994), and 3,000 Mm^3/y by the year 2020 (Ismail, 1995).

Reused Waters and Water Treatment Facilities

Introduced in the early eighties in most of the GCC countries, treated wastewater represents one of the most important alternatives that can be used to meet some of the present water requirements and to lessen the long term supply vs. demand imbalance faced by these countries. Due to completion of sewage water treatment facilities and urban sewage networks expansion in most of the GCC large cities, relatively large volumes of treated wastewater have become available, which are due to environmental considerations, have been treated completely or partially regardless of their utilization.

Table III displays the current treated volumes of wastewater, reused volumes, available facilities, and type of utilization in the GCC Countries. At present all the six countries are operating modern treatment facilities with advanced tertiary treatment capability. The total designed treatment capacity of the major facilities is more than 728 Mm^3/y, with a present total treated wastewater volume of about 720 Mm^3/y. However, the recycled volumes of these waters are about 252 Mm^3/y, which represents about 35% of the total treated wastewater. In most of the countries, the remaining unused waters are discharged to the sea. Recycling is used mainly in urban uses (irrigating gardens, roads ornamentals, etc.), fodder crops irrigation, and highways landscaping.

PRESENT CONTRIBUTION OF REUSED WATER IN TOTAL WATER DEMANDS

Table IV illustrates the utilized water resources in the GCC countries for the year 1992. As can be seen from the table that groundwater represents the main source of water supply in most of the countries (89.3%), used mainly in agriculture, and is supplemented by desalinated water (8.5%) for domestic and drinking water supply. With respect to total water supply, recycled water contribution ranges between 1.4% (Saudi Arabia) and 21% (Kuwait), with an overall average of 2.2% of the total water utilization in the GCC countries.

These figures indicate that water recycling in the GCC countries is still at its early stages. However, all the six countries have ambitious future plans for the expansion in utilization of the reclaimed wastewater as a strategically alternative source to meet their future demands. For example, Bahrain is planning to utilize 42 Mm^3/y of its tertiary treated wastewater in crop irrigation, landscaping, industry, and groundwater artificial recharge by the year 2005 (Al-Aradi, 1994); Kuwait is planing to utilize about 140 Mm^3/y of its tertiary treated water in greening and highways landscaping by the year 2010 (Al-Muzaini and Ismail, 1994); Saudi Arabia is planning to utilize about 254 Mm^3/y of these waters in Eastern Region in crop irrigation, green belts, and landscaping (Al-Saati, 1995).

MAJOR BENEFITS OF WATER REUSE

As a substitute to the limited fresh water in the GCC countries, treated wastewater has an important role to play in water resources management. In spite of some constraints, which will be discussed in the next section, treated wastewater reuse have many advantages, among which are the followings:

1. Treated wastewater can be considered as an additional source of water. While it may be restricted to specific types of use due to quality considerations, reuse in agriculture and industry will enable resources managers to reserve fresh water resources for potable supply and other priority uses.

2. With increasing population and urbanization, domestic wastewater is expected to increase proportionally, which provides an additional volumes matching the rate of development.
3. The marginal cost of providing additional good quality water of the same volume as that of the wastewater produced, will generally be higher than the wastewater. Wastewater will be produced irrespective of whether or not it is used since treatment is essential from the environmental point of view. Therefore it makes sense to reuse it as beneficially and efficiently as possible. In a recent study conducted by Al-Noaimi (1993) in Bahrain, the cost of wastewater secondary treatment was estimated to be at 0.164 US$/m^3, while its tertiary treatment cost 0.317 US$/m^3. On the other hand, desalinated water production cost in Bahrain ranges from 0.661 US$/m^3 (MSF) to 1.164 US$/m^3 (RO), with an average cost of 0.794 US$/m^3. Comparison between the costs of the two waters production indicates that it may be more economical to recycle tertiary treated wastewater than producing desalinated water.
4. Agriculture in the GCC countries is almost totally dependent on irrigation, with waters used in irrigation are averaging about 83% of the total water utilized. For these countries, which have a serious imbalance between available water resources and agricultural needs to grow food for its population, reclaimed wastewater can be considered as a source that will significantly improve the situation. These countries should grow high value crops for urban consumption as effluents are available close to urban areas.
5. In many agricultural locations in GCC countries tertiary treated wastewater quality is better than that of groundwater used for irrigation, especially in terms of TDS. Furthermore, most of soils in the GCC countries are of a sandy texture, have only traces of organic matter, and deficient in major nutrients. Treated wastewater reuse can provide low TDS water and nutrients to soil and plants, especially nitrogen and phosphorus, and thus may reduce the total requirement of commercial fertilizers, which will increase the total economic return to farmers.
6. Most of the water supplied to industry in the GCC countries is used principally for cooling. Industries can recycle their own wastewater or rely on urban treated wastewater. One of the best examples of treated wastewater utilization by industry in the GCC countries is the Riyadh Refinery. About 7.3 Mm^3/y (20,000 m^3/d) of Riyadh wastewater treatment plant effluent is pumped to the Refinery's water reclamation plant. Additional treatment is provided to produce three grades of water by the reclamation plant: 1) utility water for general cleaning, greenery irrigation, and fire-fighting; 2) process water for crude oil desalting and cooling tower use; and 3) high quality feed water for the boilers (Gur, 1995).
7. Salt water intrusion in coastal areas can be prevented by recharge of

groundwater with treated wastewater. All GCC countries' aquifers are experiencing quality deterioration due to seawater intrusion or connate water up-flow caused by over-pumping. Moreover, presently large portions of unused treated wastewater in GCC countries are discharged into the sea. For example in Bahrain, about 38 Mm^3/y of unused secondary treated water, representing about 40% of the present groundwater depletion rate of 96 Mm^3/y, are being discharged to the sea; in Saudi Arabia, over 350 Mm^3/y are being discharged to the sea and wadis. Recharging of groundwater aquifers by these unused volumes may be considered for a number of purposes, provided that they do not cause pollution to the recharged groundwater. These are: 1) It may be practiced for supplementing groundwater capacity to reduce declining levels of groundwater tables; 2) groundwater recharge may well be practiced in forming a barrier against seawater intrusion; and 3) Effluent may best be stored underground during off-season or when not used for irrigation. However, recharged treated wastewater should not be extracted before elapsing a long time in the underground (>400 days), which is needed for natural self treatment (Shuval, 1969).

MAJOR CONSTRAINTS FOR WATER REUSE

The main constraints in reusing wastewater in the GCC countries can be divided into public attitudes towards these waters reuse and technical problems that affect the quality of produced treated wastewater.

Public Attitudes

Public awareness and knowledge in the GCC countries regarding various aspects of wastewater are generally limited, which result in a generally negative public attitude toward the various uses of reclaimed water. For example, in a study conducted in Bahrain (Madani *et al.*, 1992) to assess public awareness and knowledge regarding various aspects of wastewater along with public attitude toward various specific uses of reclaimed water under different conditions, revealed that a large percentage of the surveyed individuals were not aware of the basic and simple aspects concerning wastewater. Furthermore, most respondents were strongly opposed to using reclaimed water regardless of the conditions and were willing to pay more to avoid using it. The main reasons for opposition were health risk, psychological repugnance, and religious beliefs. Knowledge and attitudes of respondents were found mainly to be dependent on the level of education and age. This survey strongly suggest that there is an immediate need in promoting public awareness and knowledge regarding wastewater in the GCC countries.

However, this general attitude has been observed to diminish in a group of farmers in Bahrain when the availability of irrigation water was in question. Due to the salinization of their irrigation water resulting from groundwater over-pumping, tertiary treated water was accepted by these farmers as an alternative source for crop irrigation. This acceptance was due to that the quality of tertiary treated water is better than the quality of available groundwater, and the reduction or absence of pumping costs as it was conveyed by the Government distribution system. With the presently observed groundwater quality deterioration trends in most of the GCC countries, it is expected that acceptance barriers for the treated wastewater will be overcome, such as the case in Bahrain.

Technical Problems

The followings are the main problems that faces treated wastewater reuse:

1. ***Microbiological pollutants*** remain the main constraint and concern over the reuse of treated wastewater effluents and its expansion in the GCC countries. Epidemiological studies carried out during the last decade (Blum and Feachem, 1985; Shuval et al., 1986) have indicated that significant occurrence of diseases were associated with raw wastewater irrigation which is caused by pathogens, particularly helminths, that are neither detected by the techniques used in conventional microbiological monitoring of effluent quality nor removed completely by conventional wastewater treatment processes. Thus helminthic infections (intestinal nematodes) poses the greatest risk to farm workers as well as to consumers of farm products, whereas bacterial infections were less important and viral infections were the least. Therefore, highest attention is paid to the removal of helminth eggs (<1 helminth egg) along with faecal coliform (<1000/100 ml) removal in the microbiological criteria of WHO Health guidelines for the use of wastewater in agriculture (Table V). Unfortunately intestinal parasitic diseases are quite widespread and endemic in several countries of the Arab World including GCC countries (Gur, 1995). It is a real challenge to engineers in the GCC countries to design conventional treatment plant which complies with the requirement of the WHO Health guidelines.
2. ***Heavy minerals accumulation in soils***. Although observed heavy minerals concentrations in treated wastewater in the GCC are generally low and below their maximum allowable limits in irrigation water, the concern remains about the accumulation of these minerals with time in the irrigated soil. For example analysis for Cd, Pb, Cu, and Zn in Bahrain's tertiary treated wastewater are 0.001, 0.007, 0.001, and 0.009 mg/L, respectively (Bahrain Environmental Protection Committee, 1991). This is compared to maximum allowable limits in irrigation (National Academy of Sciences, 1972) of 0.02, 5.0, 0.2, and 2.0 mg/L, for Cd, Pb, Cu, Zn, respectively. Under the prevailing alkaline (pH>7) desert soil conditions, certain heavy

minerals will be immobilized and their concentration will start to accumulate progressively with treated wastewater irrigation, and in many cases these metals concentrations will exceed their crucial limits, becoming hazardous to plants as well as humans. Therefore, research is needed to find methods and practices to help minimize heavy minerals accumulation in irrigated soil and to predict their accumulation rates to prevent these concentrationsZ from reaching the crucial limits. Reclamation of soils with concentrations exceeding the crucial concentration limits (i.e. reducing the heavy minerals concentration by chemical means) is difficult both technically and economically (ACSAD, 1993).

3. ***Industrial waste discharge*** in domestic waste network makes effluent reuse problematic due to the introduction of some organic and inorganic toxic substances or elevating the concentration of some constituents to a level that they would be harmful to workers and toxic for plants. Industries should recycle their wastewater, which implies that industries should be kept as much as possible in industrial zones so that their wastewater is taken care of separately and prevented from entering domestic waste networks.

POTENTIAL FUTURE CONTRIBUTION OF RECYCLED WATER IN TOTAL WATER DEMANDS

Despite GCC countries efforts in water resources conservation and provision of alternative water supplies to the different consuming sectors, there is a clear imbalance between the available water resources and water demands, which is expected to continue in the future unless some appropriate drastic measures are taken. At present, total water demands are around 22,000 Mm^3/y, with non-renewable groundwater resources satisfying about 75% of these demands, while the rest is supplied by renewable water resources, desalination plants, and recycled water (Table VI). Latest water projections for the GCC countries (Ismail, 1985) indicate that the total water demands in the GCC countries will reach about 28,000 Mm^3 by the year 2020, with an expected overall annual increase of 0.8% in total water demands. These projections take into account that water conservation and rationalization in different consuming sectors would be implemented, and surface water resources would be harvested. The projections also indicate that almost all water demands in the GCC will be met by withdrawal from fossil and renewable groundwater (87%). Furthermore, while most of the domestic water supply would be met by desalinated water and groundwater, agricultural development will continue to depend mainly on groundwater.

The projections indicate that water reuse in the GCC will increase from about 1.15% (250 Mm^3/y) of the total resources at present (1990) to about 2.33% (650 Mm^3/y) by the year 2020, with an annual percentage increase in reuse of

3.3%, the highest among other sources. However, treated wastewater volumes produced at present are already more than 650 Mm^3/y, which if recycled properly would contribute to more than 3% of the total water demands. If an assumption is made that only 50% of all domestic water supplies are treated and recycled (about 3,000 Mm^3/y) by the year 2020, then these waters would have the potential to increase their contribution by about five-folds the projected recycled water volumes of 650 Mm^3/y, and would fulfill about 11% of the total water demands in these countries. Furthermore, if these waters are used in crops irrigation, they could satisfy about 14% of the agricultural sector demands, and could reduce fossil groundwater withdrawal by about 15%.

GUIDELINES FOR WATER REUSE STRATEGY

It is essential that every country in the GCC establishes a strategy for water usage and treated wastewater reuse based on a comprehensive water resources management plan which analyzes technical, financial and economical aspects of water resources availability and use. If a country has to make a decision on effluent reuse, before such a plan is available, a focused study should be carried out which includes an evaluation on:

1. Development of alternative water supply sources to effluent reuse.
2. Efficiency of irrigation systems and feasibility of improving the efficiency.
3. Suitability of different crops and the efficiency factor of each crop in relation to different levels of treatment of wastewater.
4. Feasibility and potential benefits of installing control systems to minimize water wastage and leakage, including proper charges for water supplies.
5. Potential of effluent reuse for agriculture, industry and urban landscape irrigation including different alternatives for wastewater treatment and disposal.
6. Potential of effluent reuse for recharging groundwater aquifers to prevent salt water intrusion into the aquifers.
7. Conducting research programs to specify limits of sustainable use of treated wastewater in agriculture for long periods under varied soil types and varied crops.

Successful and efficient reuse of treated wastewater reuse in agriculture will depend on the followings:

A) ***Reliability*** of reclaimed wastewater as an alternative source for groundwater in irrigation. This could be achieved by practicing the following management strategy:

1. Practicing advanced tertiary treatment all the time to achieve quality objectives.

2. Regular maintenance and immediate repair, and upgrade of treatment plants requirements.
3. Quality assurance with excess capacity for handling peak load conditions and future growth, and avoiding sacrificing effluent quality by disposing of off-specification water.
4. Providing storage facilities (on-site, daily storage capacity near reuse sites, etc.) to balance supply and demand, achieve maximum reuse, and make supply reliable to farmers.
5. Performance and quality monitoring to enable quick response to process failures and remedial actions.

B) ***Public awareness and attitudes*** towards treated wastewater utilization. This could be overcome by the followings:
1. Public information and education programs designed to instill confidence and conducted by professionals.
2. Customer service that include users assistance program with free technical advice.
3. Building a positive image, such as using positive terminology, e.g. water recycling instead of effluent reuse, recycled water instead of treated sewage effluent or TSE.

C) ***Setting national standards*** for Reuse. The GCC countries should work on setting their own national standards that takes into account reuse economics and health development interests.

D) ***Effective Utilization.*** The present observed trend of recycling water in expanding agriculture should be re-examined. It would be more beneficial to use recycled water in existing agriculture in order to replace depleting groundwater rather than expanding agriculture. Furthermore, recycled water utilization in landscaping and ornamentals should be minimized and should be directed towards irrigating high value crops.

CONCLUSION AND RECOMMENDATIONS

1. All the GCC countries are in water shortages and water has a big potential of becoming a limiting factor for agricultural and even industrial development. Therefore, it is recommended as a matter of high priority that treated wastewater be considered and made a reliable alternative source of water in water resources management.
2. Provision of irrigation water is one of the most important factors of increasing agricultural production in the GCC countries. In all GCC countries no crops

can be grown without irrigation. Every drop of water must be carefully used in an economically feasible manner so that no higher quality water should be used for a purpose that can tolerate a lower quality. It is therefore, highly recommended that most of wastewater of domestic nature, after proper treatment should be utilized to replace groundwater in irrigation.

3. It is recommended that the following advantages of effluent reuse are kept in mind in deciding about their disposal: a) Reuse always reduces the need for chemical fertilizers; b) Reuse is a better option than disposal from the economic and environmental points of view; and 3) Treated wastewater will be produced due to environmental considerations irrespective of whether or not it is used.
4. Cost of increasing efficiencies of irrigation systems and prevention of wastage is invariably less expensive than the development of additional water resources, including effluent reuse. Therefore, it is highly recommended that priority should always be given to water conservation efforts in the field of agriculture keeping in mind that the total water used in agriculture varies between 65 and 85% of the total water utilized in the GCC countries.
5. Decision makers are recommended to consider utilizing unused treated wastewater in groundwater recharge to store water or fighting against seawater intrusion in coastal aquifers, provided that the quality of wastewater do not cause pollution of groundwater, and that recharged water are not extracted before elapsing a long time in the underground to allow for natural self treatment.
6. Mixing of industrial wastes with the general domestic wastewater for common treatment, makes effluent reuse problematic. In order to put effluent reuse away from such problems, it is recommended that industries should be kept, as much as possible in industrial zones so that their wastewater is taken care of separately by industries themselves.
7. WHO guidelines for the use of wastewater in agriculture published in 1989 specifies the effluent microbiological quality criteria (proper secondary treatment with almost complete removal of helminth eggs) for safe reuse of effluents in irrigation, providing enough health protection for farm workers and crop consumers. Therefore, for countries having no legislation on effluent reuse, it is recommended that these health guideline values may be adopted. Furthermore, GCC engineers should work on designing a conventional treatment plant that will comply with the requirements of the WHO guidelines.
8. Public awareness and knowledge in the GCC countries regarding various aspects of wastewater are generally limited, which results in a generally negative public attitude toward the various uses of reclaimed water. It is strongly recommended that promoting public awareness and knowledge regarding wastewater and its reuse in the GCC is carried out through special programs.

9. Although in general GCC countries are in their earlier stage of reclaimed wastewater utilization, some of these countries have already accumulated considerable experience and experimental research in the utilization of the reclaimed wastewater in irrigation, industry and artificial recharge. These accumulated experiences should be exchanged and shared by the six countries. Furthermore, on-going research activities in different aspects of effluent recycling should be coordinated and concerted among the six countries.

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Table I. Renewable water resources in the GCC Countries, Mm^3/y (Ismail, 1995; Al-Murad, 1994; Al-Alawi and Abdul-Razzak, 1992; Durabi, 1995; Al-Noaimi, 1993; Al-Hajj, 1995, Kuwait Ministry of Electricity and Water, 1995)

Country	Surface Water	Groundwater Recharge	Present Exploitation	Present Deficit
Bahrain	-	112	190	78
Kuwait	-	160	114[1]	-
Oman	1,450	475	728	253
Qatar	-	50	185	135
Saudi Arabia	3,210	2,340	14,430	12,090
UAE	150	120	1000	880
Total[2]	4,830	3,097	16,533	13,436

[1] abstraction by government wellfields and Kuwait oil Company only, does not include unknown abstracted volumes by private wells in agricultural areas (e.g. Wafra).
[2] Excluding Kuwait.

Table II. Desalination Plants in the GCC Countries (Ismail, 1995; Al-Alawi and Abdul-Razzak, 1992)

Country	Desalination Method		Total Capacity		Produced in 1992 Mm^3
	MSF	RO & Others	m^3/d	Mm^3/y	
Bahrain	115,000	45,000	160,000	58.4	56
Kuwait	1,409,000	-	1,409,000	514.3	240+
Oman	105,000	2,000	107,000	39.1	32
Qatar	295,000	-	295,000	107.7	83
Saudi Arabia	2,316,000	79,000	2,395,000	874.2	795
UAE	?	-	?	?	342+
Total	4,949,000	126,000	5,075,000	1,853	1,548+

Table III. Treated Water, Reused Water, Treatment Facilities, and Type of Utilization in the GCC Countries (Al-Saati, 1995; Al-Muzaini and Ismail, 1994; Al-Shaqsi, 1994; Al-Assam and Abdul-Rahim, 1994; Al-Hajj, 1995)

Country	Treated Wastewater m^3/d	Reused Water		Treatment Facilities			Type of Utilization
		m^3/d	%	Number of Plants	Total Capacity m^3/d	Treatment level	
Bahrain	154,000	25,000-30,000	16-20	1 (large)	158,000	Tertiary	Irrigating fodder crops, gardens, and highways landscaping
Kuwait	208,000	129,400	62	4 (large)	208,000 (354,000)	Tertiary	Irrigating crops, highways, coastal zones, and Kuwait zoo
Oman	20,300	10,850-17,350	54-86	2 (large) 53 (small)	24,000 50-5,000	Tertiary	Irrigating landscape areas and parks, recreational activities, and fountains
Qatar	75,000-80,000	69,000	92-86	2 (large) 9 (small)	80,000 120-3,000	Tertiary & Secondary	fodder crops, gardens, and Landscaping
Saudi Arabia	1,230,000	275,000	22	30	>1,230,000	Tertiary & Secondary	Crop Irrigation, highways irrigation, landscaping, and artificial recharge
UAE	280,000	170,000	61	4 (large)	295,000	Tertiary	Irrigating parks, golf courses, highways, and urban ornamentals
Total	1,972,300 (720 Mm^3/y)	690,750 (252 Mm^3/y)	35		1,995,000 (728.2 Mm^3/y)		

Table IV. Summary of Exploited Water Resources in the GCC Countries, 1992 (modified[1] after Al-Alawi and Abdulrazzak, 1993)

Country	Groundwater		Desalinated		Recycled		Total
	Mm^3/y	%	Mm^3/y	%	Mm^3/y	%	Mm^3/y
Bahrain	160	71.4	56	25.0	8	3.6	224
Qatar	144	57.6	83	33.2	23	9.2	250
Kuwait	80	19.8	240	59.6	83	20.6	403
Oman	645	93.8	32	4.7	10.5	1.5	687
Saudi Arabia	14,430	93.5	795	5.1	217	1.4	15,442
UAE	900	69.0	342	26.2	62	4.8	1,304
Total	16,359	89.3	1,548	8.5	403.5	2.2	18,310

1 modification is made for Bahrain recycled figures

Table VI. Present and Projected Future Water Demands in the GCC Countries in Mm^3/y (Ismail, 1995)

Demands/Resources	Estimated 1990	Projected 2020	% Expected annual increase
Water Demands			
Domestic	3,400	6,100	2.0
Agricultural	18,000	21,000	1.7
Industrial and Social	350	750	2.6
Total Water Demands	**21,750**	**27,850**	**0.8**
Water Resources/Sources			
Fossil Groundwater	16,400	20,200	0.7
Renewable Groundwater and Surface Water	3,000	4,000	1.0
Desalinated Water	2,100	3,000	1.2
Reused Water	250	650	3.3
Total Resources/Sources	**21,750**	**27,850**	**0.8**

Table V. Recommended Microbiological Quality Guidelines for Wastewater Use in Agriculture (WHO, 1989)[1]

Category	Reuse Conditions	Exposed Group	Intestinal nematodes[2] (arithmetic mean no. of eggs/ liter[3])	Faecal Coliforms (geometric mean no. / 100 ml[3])	Wastewater treatment expected to achieve the required microbiological quality
A Unrestricted	Irrigation of crops likely to be eaten uncooked, sport fields, public parks[4]	Workers, consumers, public	<1	<1000[4]	A series of stabilization ponds designed to achieve the microbiological quality indicated, or equivalent treatment
B Restricted	Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees[5]	Workers	<1	No standard recommended	Retention in stabilization ponds for 8-10 days or equivalent helminth and faecal coliform removal
C Localized	Localized irrigation of crops in category B if exposure of workers and the public does not occur	None	Not applicable	Not applicable	Pretreatment as required by the irrigation technology, but not less than primary sedimentation

[1] In specific cases, local epidemiological, socio-cultural, and environmental factors should be taken into account, and the guidelines modified accordingly.
[2] *Ascaris* and *Trichuris* species and hookworms.
[3] During the irrigation period.
[4] A more stringent guideline (<200 faecal coliforms per 100 ml) is appropriate for public lawns, such as hotel lawns, with which the public may come into direct contact
[5] In the case of fruit trees, irrigation should cease two weeks before fruit is picked, and no fruit should be picked off the ground. Sprinkler irrigation should not be used.

Securing a Blue Transformation Via a Global Freshwater Convention

Anthony Milburn

SECURING A BLUE TRANSFORMATION VIA A GLOBAL FRESHWATER CONVENTION

Anthony Milburn
International Association on Water Quality (IAWQ)
London

ABSTRACT

This paper identifies three major challenges facing the global freshwater sector:

- the mass of the public around the world is unaware of the challenges facing the freshwater sector. As a result public opinion on the issue is lacking and most countries generally do not recognize water issues as a high priority.
- there is a vacuum of initiative in the freshwater sector, at national, regional and international levels. This contributes also to the lack of concerted action by countries on freshwater matters.
- in order to meet the growing demands being made on the world's freshwater, which are of finite quantity, a huge increase in productivity is needed.

Overall a blue transformation is needed in the way mankind manages its freshwater, to secure the huge increase in productivity of freshwater usage needed for next century and to establish sustainable exploitation of water resources. AGENDA 21, Chapter 18 on Freshwater has recommended what is needed - integrated water resources management, based on catchment basins or sub-basins as the management unit. Thus a series of measures is proposed to begin to implement AGENDA 21's recommendations and get the blue transformation under way. The catalyst for the needed changes would be a new global Freshwater Convention, with initially three principal objectives:- a) arousing public attention, b) focusing political will for executive action at international, regional and national levels, c) setting up a programme for the widespread establishment of Basin Management Agencies or Committees (for rivers and lakes) to carry out the necessary integrated basin management. In addition an international public relations exercise is recommended, led by a team of "champions", to promote the cause of the "blue transformation". This would extend also to the international and regional trade organizations, recognizing the crucial links between economic activity and the environment. The public relations campaign and the Convention would help to arouse public opinion and exert pressure for change. The proposed Global Freshwater Commission and the Basin Management Agencies/ Committees would provide much of the leadership. And the application of the recommendations of AGENDA 21, Chapter 18 on Freshwater, allied to the attitude and behavior changes expected of the arousing of public opinion, plus the leadership of the Commission and Basin Management entities, would begin to secure the blue transformation in productivity of freshwater use.

BACKGROUND

The water resources challenges facing mankind in the next century are vast and are poorly appreciated by the world's population. Hence there is little perceived urgency to begin to take the much needed steps to provide freshwater security to a rapidly increasing and urbanizing world population.

The present situation has parallels with the potential food shortage situation which faced the world in the second half of the present century. That challenge was met by the "Green Transformation". By dint of improved farming practices, plant breeding, irrigation, fertilizers and pesticides, etc. the required huge increase in food production was achieved.

What is needed now is a "blue transformation", to bring about a parallel massive increase in productivity of usage of the world's freshwater. Attitudes and behaviors towards freshwater usage must be changed and systems for the sustainable exploitation of an increasingly scarce resource put in place. An important element in this will be the concepts set out in Chapter 18 of AGENDA 21 on a) the integrated management of water resources, and b) that such management should be carried out at the level of the catchment basin or sub-basin. Thus the early establishment of Basin Management Agencies (or Committees) for both river and lake basins will be one of the priorities. The reasons for this will become apparent later in this paper when it is pointed out how many of the world's freshwater basins are shared by more than one country.

CHALLENGES OF FRESHWATER MANAGEMENT

The overall theme is one of growing competition for a finite resource, combined with inefficient, harmful and frequently wasteful usage. Fundamental to the competition for freshwater are: a fast growing population with rising expectations of quality of life and food consumption; expanding industrial activity; increased energy needs (hydropower included); widespread urbanization with a concomitant increased demand for water, and a variety of others. Furthermore, in many parts of the world, responsibility for freshwater management is fragmented and inefficient.

Looking at some of these issues in more detail:

- little attention is paid to combined land/water use policy. Irrigation usage is often inefficient and at times positively harmful in terms of salinated soils and poor quality drainage water. Urban areas waste vast amounts of water through badly functioning utilities. And industrial and municipal effluents and agricultural runoff are causing widespread and serious deterioration of water quality; not only is mankind threatened by water quality deterioration, but also the natural aquatic ecosystems of many parts of the world;

- the world population continues to increase apace. During the past century the world's population tripled and water usage grew tenfold. On present estimates the world population is expected to grow a further 45%, from its current level of 5.7 billion, causing a further huge increase in water demand. All of this emphasizes the immediate urgency for a new global water strategy;[1]
- a high proportion of the world's water resources are in river or lake basins shared by more than one country. Such shared basins make up nearly 50% of the Earth's land area and some 60% of the area of both Africa and Latin America.[2] Currently almost 50% of the world's population lives in shared river or lake basins and it is estimated that there are some 214 river basins shared by more than one country.[3] Water shortage problems are growing. By definition, water shortage occurs when freshwater availability falls below 1700 m^3/capita/year. By 2050 some forecasts have estimated that 65 countries will face water shortages and that 65% of the then projected world population will be affected, most of them in developing countries;[4]
- the worldwide incidence of waterborne disease remains high. Faecal contamination of water supplies, poor sanitation, inadequate domestic hygiene practices, malnutrition and lack of vaccination all contribute to this, but contaminated water supplies are a major source of the problem;
- within many countries responsibility for freshwater management is divided between several ministries, often with little coordination or cooperation. Division of responsibility for freshwater affairs is also apparent in agencies. As AGENDA 21 Chapter 18.6 has pointed out:

  > "The fragmentation of responsibilities for water resources development among sectoral agencies is proving to be an even greater impediment to promoting integrated water management than had been anticipated".
- frequently there is a serious lack of a national water resources management policy and, in the case of shared water resources, limited cooperation, if any, between riparian states to secure effective use of resources. The World Bank's Economic Development Institute has recommended National Water Strategy Formulation as one of four key criteria in water resources management.[5] However in the large number of shared basins around the world this can only be effective in collaboration with other riparian states and few mechanisms exist for the needed consultation and coordination;
- water is low on the political agenda of very many countries;
- it is widely accepted that, in water scarce areas, especially where tensions are high for other reasons, the risk of armed conflict over shared water resources is looking evermore likely.

The above emphasizes how interdependent much of the world is set to become, in freshwater as in so many other areas of life. It points to the need for cooperative action and a big increase in efficiency.

THE BLUE TRANSFORMATION

OBJECTIVES

The principal objectives of the blue transformation would be to bring about the needed changes in attitude and behaviors in order to ensure that adequate freshwater of the right quality is available both for mankind and the rest of the planetary ecosystem. If successful, there would be a huge increase in the productivity of freshwater usage.

Looking at the objectives in more detail, the blue transformation would seek the following:

Attitude Changes:

- to raise awareness worldwide about the principal issues in freshwater - pollution, wasteful use, the finite extent of available freshwater, threat to natural aquatic ecosystems
- to create in each citizen a sense of personal responsibility towards freshwater conservation and preservation
- to provide a climate for water resources sharing among nations in ways which have not been widespread before
- by mobilizing public opinion, encourage local, national, regional and international administrations to move freshwater issues high up the agenda

Behavior Changes:

- to introduce integrated water resources management at catchment basin level, taking account of integrated land use/water management
- to prevent wasteful water use practices in agriculture and industry
- to introduce efficient utility usage of freshwater
- to minimize or prevent water pollution by industry, municipalities and poor agricultural practices
- to encourage technological innovation for more efficient usage of freshwater in agriculture, industry and domestic/municipal settings.

A VISION FOR FRESHWATER USAGE

Modern approaches to corporate strategic planning emphasize the need for a vision statement, which is then augmented by a more comprehensive mission statement. For the vision it is difficult to find a more eloquent and inclusive one than that of AGENDA 21 Chapter 18.2:

> "Water is needed in all aspects of life. The general objective is to make certain that adequate supplies of water of good quality are maintained for the entire population of this planet, while preserving the hydrological, biological and chemical functions of ecosystems, adapting human activities within the capacity limits of nature and combating vectors of water related diseases".

THE FRESHWATER MISSION STATEMENT

A comprehensive mission statement, taken again from Chapter 18, would comprise:

a) Need for Integrated Management:
"The widespread scarcity, gradual destruction and aggravated pollution of freshwater resources in many world regions, along with the progressive encroachment of incompatible activities, demand integrated water resources planning and management. Such integration must cover all types of interrelated freshwater bodies, including both surface water and groundwater and duly consider water quantity and quality aspects. The multi-sectoral nature of water resources development in the context of socio-economic development must be recognized as well as the multi interest utilization of water resources for:- water supply and sanitation; agriculture; industry; urban development; hydropower generation; inland fisheries; transportation; recreation, low and flat lands management and other activities" Agenda 21, Chapter 18.3.

b) Need for Management at Basin Level:
"Integrated water resources management, including the integration of land and water related aspects, should be carried out at the level of the catchment basin or sub-basin" Agenda 21, Chapter 18.9.

c) Need for Harmonization by Riparian States:
"In the case of trans-boundary waters there is a need for riparian states to formulate water resource strategies, prepare water resource action programmes and consider where appropriate the harmonization of those strategies and action programmes" Agenda 21, Chapter 18.10

d) Need for Demand Management and Economic Tools:
"The role of water as a social, economic and life sustaining good should be

reflected in demand management mechanisms and implemented through water conservation and reuse, resources assessment and financial instruments" Agenda 21, Chapter 18.17.

e) Need for River Basin Management Systems:
World Bank Vice President, Ismael Serageldin [6] has added his thoughts to the above and focused on the concepts of river basin management agencies or committees as a model for planning freshwater use, with other entities or utilities carrying out the actual work of freshwater delivery:

> "Water must be managed comprehensively. We must stop managing water sectorally - by its separate uses - and begin to treat water systemically; that is inter-sectorally. We have learned about the benefits of developing a comprehensive framework for water resources management that recognizes the interactions between various elements of a river basin's ecosystem and allows for the incorporation of cross sectoral and environmental considerations in the design of investments and policies. Here the French and German systems of river basin management could serve as models. Under these systems, river basin committees decide long terms plans for developing water resources. Regulation and enforcement are conducted by various national ministries, while operation and maintenance of the different components are left primarily to regulated private entities and public utilities".

f) Need for Peaceful Cooperation Among Riparian States:
In his address to the 1994 Cairo World Water Resources Conference, Mahmoud Abu Zeid [2] made the following recommendations:

> "While there are numerous treaties regulating the use of shared water resources, international agreements are often either inadequate or lacking entirely in some parts of the world where a water basin (river or lake) is in greatest demand. No region in the world with shared international waters is exempt from water related controversies though the most serious problems occur in water scarce regions. The key to peaceful solutions of disputes over shared water resources is continued communications between the states concerned, over everything from hydrologic and meteorological data to basin wide development plans".

Whilst peaceful cooperation among riparian states is the ideal situation, it is inevitable that disputes will arise. However, as Sandra Postel has pointed out, although more than 200 rivers are shared by more than one country,.... "no enforceable law governs the allocation and use of international waters". [3]

A PLAN FOR ACTION

THE MAIN COMPONENTS

From the foregoing, the challenges are clear, and formidable. AGENDA 21 has projected the vision. And AGENDA 21 and key international experts have articulated the main components of the mission which needs to be carried out. What is needed is a plan to carry through the blue transformation with the needed practical steps.

Central to this plan and acting as a catalyst for change, would be a new Global Freshwater Convention, consisting of both a Freshwater Treaty and a Global Freshwater Commission. Augmenting the Convention and motivated by it would be a programme for the widespread, early establishment of Basin Management Agencies or Committees. The final element, although it may need to be the first to be carried out, would be a global public relations campaign to urge the whole process forward.

Why a Convention? Experience in other sectors (and, interestingly most other sectors of the environment except freshwater have now or will have shortly Conventions, treaties or protocols) have shown that Conventions:

- attract widespread media attention and publicity, sensitize the public to the issues involved, mobilize public opinion in favor of the needed changes and begin to bring about major changes in thinking and behavior
- bring public opinion and concern to the attention of administrations at international, regional and national levels

Conventions have been shown to be effective in changing attitudes and behaviors on an international scale. They act as a symbol via which public opinion is mobilized, a focus for subsequent administrations and a banner under which needed change is carried out. Today, few other devices, if any, are known to be as effective in making changes at global scale in a reasonably short time.

Given the challenges facing the freshwater sector it is difficult to see what other means could activate the blue transformation and achieve the needed changes within the required time frame. And, thereafter, provide an appropriate framework for the care and sustainable and equitable use of the world's freshwater, well into the future.

A GLOBAL FRESHWATER CONVENTION

This would consist of a new Global Freshwater Treaty, of the framework type, and a new Global Freshwater Commission. The purpose would be to focus on means of managing the world's freshwater in an equitable, integrated sustainable way, recognizing the catchment basin or sub-basin as the appropriate level for such integrated management and the high level of interdependence of the world's population living in shared basins rivers, lakes and underground aquifers. A key would be to minimize bureaucracy and to seek to create an appropriate enabling environment for integrated water resources management to flourish in the many different forms which will emerge. The Convention should be crafted so that, not only can it embrace a framework for getting the blue transformation under way, but it can also provide a structure within which mankind can protect and exploit freshwater both equitably and sustainably, far into the future.

It has been argued that a freshwater convention would be difficult and time consuming to achieve, that countries would oppose it because water is seen as a national issue. Yet nearly 50% of the world lives in shared water basins now and this percentage is likely to rise with population increase. And once public concern about freshwater is mobilized, the pressure for a convention to protect and preserve freshwater for future generations is likely to be irresistible.

A crucial point to realize is that whereas water shortages may not be universal, water quality problems are worldwide, are bad and getting worse. Even in the European Union where expenditures on water protection are huge, progress towards significant water quality improvement is slow. A Freshwater Convention would be designed to secure sustainable exploitation of the world's freshwater. Unless all countries agree to programmes of water quality protection, and a Convention is one way to seek this, their citizens cannot enjoy sustainable water use in the future.

Funding will be required to support the work needed for the Convention. Whereas initially this will need to come from the UN and supporting governments, the arrangements of the Law of the Sea Convention merit examination. That Convention has a Treaty, a Commission and a commercial arm. The latter is interesting. It raises money through the issue of licenses for mineral exploitation of the sea bed. Clearly the Freshwater Convention could not imitate this directly. However freshwater activities worldwide involve multi-billion dollar expenditures and it seems feasible to consider a levy on major water users to raise the needed funds. Certainly this should be examined carefully so as to eventually move the Convention away from dependence on agency or government funding.

A GLOBAL FRESHWATER TREATY

This must be a framework treaty, setting down the main principles, but flexible enough for regional interpretation because of the very diverse nature of water resources systems worldwide. It is not proposed here to go into the detail of what it should contain but rather to point at certain general principles and also indicate some relevant initiatives in progress at present. In general the Treaty would include provisions for sustainable qualitative and quantitative exploitation of water resources. It would recognize the huge interdependence of nations on shared resources and would emphasize the need for equitable and reasonable utilization and the need to avoid harm to a resource. It would highlight the need for formal arrangements to promote fair use of shared resources and make provision for resolution of disputes.

As far as international watercourses are concerned the UN International Law Commission (ILC) has recently submitted to the UN General Assembly a new set of "Rules on the Non-Navigational Uses of International Watercourses". These contain 33 articles covering such principles as: watercourse agreements; equitable and reasonable utilization and participation; obligation not to cause harm to other watercourse states; general obligation to cooperate; obligations to notify other watercourse states about planned measures; protection and preservation of ecosystems; prevention and control of pollution; protection/preservation of the marine environment; management; regulation; settlement of disputes etc. These Rules have been reviewed by member states, and a working group from the General Assembly will revise them late 1996. The ILC has requested then that the General Assembly should convene a conference to discuss the production of a convention based on the Rules. The ILC has specifically cast the Rules in framework form, so that they are flexible enough for interpretation in the light of different regional circumstances.

Elsewhere the Global Programme of Action for Protection of the Marine Environment from Land Based Activities (GPA) agreed an Action Programme at a meeting in Washington DC in November 1995. Adopted by more than 100 governments, the Programme aims to protect seas from pollution generated on coasts and far inland. It is currently addressing 2 priority areas: i. the proper treatment of urban waste water and sewage; ii. development of a global legally binding instrument on persistent organic pollutants. Both of these are of great importance not only to coastal seas but also the freshwater systems which drain into them.

Both the Rules and the GPA could be included, as appropriate, in a Global Freshwater Convention.

In Europe two initiatives offer guidance on how a region may actually go about implementing agreements on freshwater usage. Firstly, the UN Economic Commission for Europe (ECE) has adopted a Convention on the Protection and Use of Trans-boundary Watercourses and International Lakes. It is orientated to water quality issues and will come into force during 1996. Implementation is based on intended cooperative agreements between countries bordering the same waters.

Secondly, within the European Union (EU), the European Commission has recommended the development of a comprehensive strategy on freshwater and seas. This will set out an integrated planning and management approach to groundwater and surface water resources, which will focus on both quantitative and qualitative aspects of Europe's freshwater and will ensure also a sustainable management of regional European seas. The intention is to issue, in draft form, a Framework Directive for a European water resources policy in late 1996, with possible implementation by the year 2000.

The European examples are important, for two reasons. Firstly they show that a major politically and economically interdependent region has chosen already the route of Convention and Directive for its freshwater management. Secondly they suggest that other economically dependent regions (existing or becoming so) could have the necessary foundations for effective implementation of the Freshwater Convention, e.g. ASEAN in SE Asia, MERCOSUR in Latin America, or The Arabian Peninsula as a hydrological unit, etc.

GLOBAL FRESHWATER COMMISSION

Its function would be to administer the implementation of the Treaty and promote and assist in the setting up of Basin Management Agencies or Committees (BMAs), including identifying and channeling needed financial assistance. The initial priority for setting up such Agencies or Committees would be in regions of water shortage, particularly those nearing crisis point and where armed conflict is possible. In addition the Commission would ensure the provision of machinery for settling disputes, using existing institutions where feasible, such as the International Court of Justice, but also making provision for arbitration and maybe establishing an International Tribunal on Freshwater Issues. The Commission would seek to identify and promote Best Management Practices (BMPs) for the sustainable exploitation and management of freshwater. It would also identify research and training needs, then promote action to meet these needs. The Commission would seek to influence international and regional trade organizations to make freshwater protection a key element of their activities.

The composition of the Commission would be crucial. A big challenge to the Commissioners would be to broker agreements among riparian states to set up Basin Management Agencies or Committees. Commissioners would need to work at the highest levels of government, including heads of state. They could also be called upon to assist in dispute resolution and influence the allocation of funds from donor agencies. Thus it is vital that Commissioners be persons of influence and very high personal standing. They would provide the much needed leadership which is seriously missing at present [8].

Among the Commission's resources would be a small permanent staff, chosen from a wide range of organizations, including the private sector. However, the intention is not to establish a significant bureaucracy but rather to provide the necessary minimum staff to service the Convention. Thereafter the Commission would tap into the resources of the wide range of existing organizations, individuals and institutions in the many parts of the freshwater sector. These would include the Global Water Partnership, World Water Council, UN agencies, banks, international and national water professional associations, universities, the expertise within existing river basin agencies, bilateral aid agencies etc. A major challenge to the Commission would be to encourage these different organizations to view freshwater management more holistically, rather than the fragmented approach adopted to date. Almost certainly a new "water think tank" institution would be needed, but it is understood that such an initiative is presently under discussion.

A further challenge facing the Commission would be dealing with the concept of water sovereignty or "our water". In a very interesting recent project in the Middle East [9] a team of economists, water specialists and negotiators were able to move thinking away from the traditional conservatism about water sovereignty towards ideas of water values and water markets. A model was produced which will enable the countries concerned to trade available freshwater to their mutual benefit and to attain further benefits from regional management of freshwater which would not have been possible with a national management approach. Some important concepts are involved in this with potential for further and wider application, but more work is needed to evolve them further. Certainly water sovereignty issues, economic concepts such as those above and other aspects of water markets and economic activity will all play key roles in future freshwater management concepts. Trading activities involving water may not be restricted to water but could include other commodities, e.g. power.[3]

In all of this, one of the prime roles of the Commission would be to provide leadership. Emphasizing the points made in the Introduction to this paper, one of the reasons why freshwater management is fragmented and why it suffers from relatively low recognition, is attributable to a lack of leadership. Looking to the future, the freshwater sector could continue largely as it does now and wait for the crises and wars to erupt. Then leadership will have to emerge, to mediate the conflicts this is reactive leadership. Or, by the means suggested in this paper, proactive leadership can be exercised, the blue transformation pushed forward and most of the crises/wars averted. This is a highly important point because it highlights that mankind does indeed have a choice and has the opportunity to seize the initiative of proactive leadership.

RIVER BASIN MANAGEMENT AGENCIES OR COMMITTEES

The main principles which should guide basin management systems have been laid down in AGENDA 21 Chapter 18.9. The stress is on integrated water resources management, including the integration of land and water related aspects. The advice is to carry out water resources management at catchment basin or sub-basin level and that the following principal objectives should be pursued, as follows:

a) To promote a dynamic, interactive, iterative and multi-sectoral approach to water resources management, including the identification and protection of potential sources of freshwater supply, that integrates technological, socio-economic, environmental and human health considerations.
b) To plan for the sustainable and rational utilization, protection, conservation and management of water resources based on community needs and priorities within the framework of national economic development policy.
c) To design, implement and evaluate projects and programmes that are both economically efficient and socially appropriate within clearly defined strategies based on an approach of full public participation, including that of women, youth, indigenous people and local communities in water management policy making and decision making.
d) To identify and strengthen or develop as required in particular in developing countries, the appropriate institutional legal and financial mechanisms to ensure water policy and its implementation as a catalyst for sustainable social progress and economic growth.
e) In addition, in the case of shared basins, there is the need for harmonization of water resources strategies among riparian states Chapter 18.10.

The above are the principles. In terms of actually setting up and evolving the Basin Management Agencies or Committees, Stockholm Water Prize laureate Madhav Chitale has offered some thoughtful guidance.[10]

> "Rather than aiming at a standardized set up for all international river basins, basin organizations can best be allowed to grow in phases according to the needs of the respective basins. The nature of the basin organization

and its stage of evolution will dictate the type of personnel required. These organizations will have a federal set up to represent the interests of all stakeholders. Even though the governance of these organizations will be by a body of political representatives of the participating countries, the technical and professional wings should have the necessary freedom of action in their normal work. For healthy working of river basin management committees, negotiations between the participating countries will be the principal thrust. Still a provision for arbitration for resolution of disputes will be desirable".

These words emphasize the likely wide variation in character of basin management entities, depending not only on the particular circumstances of a basin but also the status of development of the riparian states and the activities carried out within the basin. Thus some basin management entities may be advisory committees whereas others would function as executive agencies including carrying out programmes.

Generally however as Serageldin [6] pointed out in the examples of French and German Basin Management Agencies, the priority would be to set policy and produce an enabling environment, including regulatory framework, for other agencies and utilities to carry out the actual freshwater exploitation programmes.

Privatization of such programmes will continue to be of growing importance in many basins. Privatization of the executive capacity of a particular Basin Management Agency should also be an option, where appropriate. In addition, as with the suggestion for the Global Freshwater Commission, it may be possible eventually for Basin Management Agencies to recover their costs from a levy on major freshwater users.

It is possible to foresee an Agency at some time in the future where trade and privatization are the dominant features. For example:

- the Agency is located in a free trade area which has strong freshwater protection programmes
- whilst the Board of the Agency consists of elected representatives, day to day management is by a private company. It uses a range of market mechanisms and economic tools to allocate freshwater and control water quality ("water trading and polluter pays" principle)
- all the major freshwater uses are privatized e.g. water and wastewater utilities, industry, hydropower, irrigation water supply companies, transport companies etc.
- volumes of water are traded within the Basin or with adjoining Basins using water and other commodity exchanges (e.g. power) as barter.

CAMPAIGN/PUBLIC RELATIONS INITIATIVE

At the beginning of this paper the lack of public perception and absence of serious concern about the magnitude of the looming freshwater challenges was highlighted. A major initiative is needed to educate the public about the issues involved and mobilize public opinion in support of the blue transformation. Experience in other sectors and with other important global issues, e.g. famine, poverty, etc. suggests that a campaign led by some highly prominent, respected international figure, or better still, group of figures, could achieve the desired effect. He/she or they would "champion the cause". If effective this could bring about the necessary pressure at national and international level and bring about reasonably speedy implementation of the Treaty, the setting up of the Commission and the BMAs and the crucial initial objective of achieving systems for the sustainable management of the world's freshwater. One of the challenges then is to identify the person(s) to lead such a campaign and secure his/their commitment to action.

A significant proportion of the campaign would be carried out in developing countries. The successful water promotions in Morocco and India have shown how this can be done.

Also needed is a concerted program to alert the World Trade Organization and the regional free trade areas to the problem of freshwater and urge them to take action to deal with these, both internationally and regionally.

PRIORITY ACTIONS

A number of initiatives to get the blue transformation under way could begin very quickly, acting on a number of fronts in parallel:

- seek the help of international citizens groups and organizations to promote the cause of freshwater protection through their national chapters e.g. women's and children's movements, religious organizations and environmental law associations
- look carefully at the water campaigns in Morocco and India and see if these could be replicated elsewhere
- send high level delegations of water experts to the WTO/GATT and the regional free trade organizations and seek commitment from them to give high priority to freshwater matters
- urge the UN Commission on Sustainable Development to recommend two actions to the UN General Assembly in 1997:
  the promotion of a Global Freshwater Convention

the setting up of an Intergovernmental Panel on Trade and Environment with freshwater high on its agenda.

CONCLUSIONS

The ideas proposed in the paper have been tried and tested elsewhere. Thus there is every reason to believe they can work for freshwater too. Most of the ideas are based on AGENDA 21's recommendations.

A growing number of people around the world are questioning why there is no convention or treaty for freshwater. They compare water with other environmental sectors and see virtually all of them protected by convention, treaty or protocol. Yet freshwater, the life blood of planetary systems, has lagged behind.

Some water professionals question the need for a convention. They say that water is a national issue, that water shortages are localized, that "convention fatigue" is apparent among governments. Yet it is accepted that there is no body of international law to deal with freshwater disputes. And while present water quantity problems are regional, they are becoming more widespread. Moreover water quality is deteriorating alarmingly in most parts of the world. If we are to have usable freshwater for future generations and avoid water wars, governments must commit themselves to freshwater protection. The proposed Global Freshwater Convention is the obvious way to do this.

Furthermore the freshwater sector needs leadership. It needs it at international level and at basin management level. The proposed Global Freshwater Commission would provide international leadership. The River or Basin Management Agencies would provide the leadership at basin level. The present fragmentation of responsibilities would be overcome.

The crucial linkages between economic activity/trade and the environment have been emphasized. Given that the WTO/GATT system and the regional free trade areas nearly all have commitments to environmental protection, this needs to be exploited. These trade organizations must be informed about the challenges of the freshwater sector and a commitment obtained from them to give freshwater issues high priority.

The support of concerned citizens' groups must be sought, to assist in the promotion of awareness of freshwater's problems among the world's public. International NGOs for women, children and the various churches would be very supportive. They all have natural concerns about the future and the security of coming generations, as well as a sense of responsibility and caring about vital issues.

Time is short. Population increase will not stand still while arguments continue about whether there should be a convention or not. Competition for increasingly short supplies of water will not diminish, nor will continued deterioration of water quality. In order to secure a suitable framework of international freshwater law, for the resolution of disputes etc.; in order to get governments to commit to protecting freshwater for future generations; in order to change behavior and attitudes to freshwater, there is little serious alternative to a Global Freshwater Convention. Thus action to set up and implement the Convention is needed soon. All of this will be central to the bringing about of the blue transformation.

This paper is not a blueprint for the action needed for freshwater. It does not propose any quick fix solutions, because there are none. Rather a framework is proposed. Many of these ideas are concerned with getting change underway, particularly attitude change and with getting certain priority activities started. It is accepted that much more needs to be done.

The final point is that the blue transformation is not an option. It is not a fancy slogan to catch the attention of the media and the general public, although it could become the motto and indeed the rallying cry for change. This paper has indicated ways of bringing about that change public education to secure attitude/ behavior change; lobbying trade organizations to include freshwater protection in their policies; provision of leadership via the Global Freshwater Commission and the Basin Management Agencies; bringing all of this together via the proposed Freshwater Convention. However, whether these or other courses of action are pursued, the blue transformation is not an option; it is a necessity. Should mankind fail to react to this fact, then the consequences will be dire indeed.

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Water Security in the Kingdom of Saudi Arabia

Mohammed H. Al-Qunaibet

WATER SECURITY IN THE KINGDOM OF SAUDI ARABIA

Mohammad H. Al-Qunaibet
King Saud University
Riyadh, Saudi Arabia

ABSTRACT

Media coverage of water security issues in the GCC countries and the Kingdom in specific has been intesifying in recent years. However, most coverage and analysis concentrated on the strategic ground water reserves in the Kingdom. Nevertheless, not much attention has been given to the question: *how much water has been withdrawn from these strategic ground water reserves?* in order to confirm or deny the existence of such a water security problem in the Kingdom.

This paper will try to estimate the amount of water used in the agricultural sector in the Kingdom during the period 1980-1995 through the calculation of crop irrigation requirements and comparing the resulting figure with the proven ground water reserves. Finally, this paper will look into a strategic plan to conserve and preserve the ground water resources inthe Kingdom.

Results showed that in the period 1980-1995 the Kingdom has pumped around 254.5 billion cubic meters of ground water to satisfy the agriculture sector's needs which amounts to 75.4% of the proven ground water reserves in major aquifers or 51% of the proven ground water reserves in major and secondary aquifers. This huge pumping of nonrenewable strategic ground water reserves in a country where no surface water available, scarce rainfall, and very harsh desert climatic confirms the critical situation of the ground water reserves in the Kingdom which requires a swift implementation of a strategic national water plan that will ensure the preservation of whatever left of these invaluable and nonrenewable water resources.

Such a strategy centeres on the urgent need for the creation of an independent ministry of water resources that has full authority to draw and instigate a national water plan to conserve and preserve water resources. Other recommendations in such a strategy include: (1) extensive and quick hydrological survey to update the correct outstanding strategic ground water reserves in major and secondary aquifers, (2) banning exports of water-intensive crops such as dairy products

and fodder, (3) discontinuing the support of water-intensive crops that can be imported cheaper, (4) stop issuing new permits for fodder projects and discontinuing all support and subsidy programs to existing fodder projects, and (5) introducing price mechanism to reduce water consumption in the agriculture sector.

THE ROLE OF INFORMATION SYSTEMS IN THE MANAGEMENT OF URBAN / INDUSTRIAL WATER CYCLE

H. Ludwig and K. D. Wolz
Fichtner, Sarweystrasse 3, 70191 Stuttgart, Germany

ABSTRACT

The availability of water has already become, in many regions of the Earth and particularly in arid regions, a limiting factor for population and industrial development. The increasing scarcity of water, but also the rising water needs of population and industry require a rethink, away from the resource water of unlimited availability to a commodity to be considered under quality and cost aspects. The high costs of the generation of fresh water suitable for drinking water and industrial service water (for example by seawater desalination) have already led in the past in those countries dependent on such external resources, to the reuse of waste water for land irrigation in towns, communties and regions, but also to waste water reuse and recycling in major industrial complexes. Thrifty utilization of the increasingly valuable resource water implies:

- minimization of water consumption and use in line with the quality requirements of consumers
- furthergoing reuse and recycling of industrial waste water
- furthergoing treatment of effluent from municipal sewage treatment works for its utilization in irrigation or by consumers in municipalities and industry with low quality requirements

These measures, including the utilization of sewage sludge for agriculture customary in many countries of the arid zone results in mutually dependent cycles, referred to as the urban/industrial cycle, which particularly in arid regions can react very sensitively to the addition of enhanced salt and heavy metal contents from industrial discharges.

By adopting appropriate information and monitoring systems, the industrial and municipal aspects of this cycle is to be monitored and controlled. In this way, any changes in, for instance, the quality of irrigation water and sewage sludge can be countered in good time. Furthermore, basic information for planning municipal and industrial expansion projects is available.

The increasing scarcity of the resource water can no longer be countered by technological measures oriented to individual cases. Modular environmental and operating data information systems can, when integrated into corresponding management structures provide decisions aids and a basis for planning. Then by specific treatment measures can achieve a reliably interplay between the industrial and municipal water, waste water and sewage sectors.

Keywords:
Treatment measures for sewage effluents
Segregation, reuse and recycling of industrial waste water,
Reuse of municipal sewage effluent
Urban/industrial cycle
Monitoring and management systems for industry and municipalities

AVAILABLE WATER RESOURCES AND TECHNICAL MEASURES TO OPTIMIZE ITS USE

For economic and industrial development, alongside energy, raw materials and foodstuffs, water is today, and even more in the future, one of the decisive factors. Whereas in the major industrial nations of Earth's northern hemisphere, the costs for treatment and provision of drinking water and industrial service water for the population and industry are the critical parameters with regard to urban development and industrial growth, in many other regions of the world, in particular in arid regions, the availability of water from natural resources is already today the limiting factor in the development of their population and economies. In part, industrially further developed countries of the arid zone are already reaching their limits in the extraction of fresh water from natural ground water and surface water resources. Hence, in particular in the countries of the Arabian Gulf, but also in the industrialized regions of North Africa, the natural resources are no longer enough to supply the population with water (Fig. 1). In those countries which still have adequate natural water resources, up to not too long ago, drinking water from the municipal water supply system together with ground water almost to drinking water quality, or requiring relatively little treatment outlay, were the principal resources for the provision of industrial service and process water.

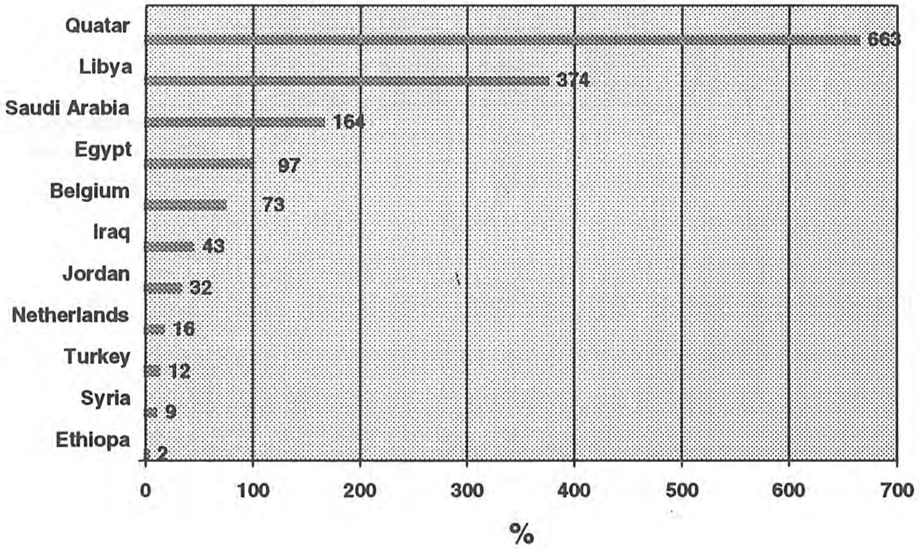


Figure 1. Proportions of fresh water from internal and external sources

The cost pressure resulting from increasingly stringent requirements for waste water discharge as well as the growing costs of drinking water treatment have, however, also led in these countries to consideration of ways of saving water, the reuse of waste water, and recycling of water in closed circuits. The result is shown in the statistics for industrial water consumption and water extraction of Western German industry where despite an approximately three-fold increase of water consumption between 1975 and 2010, water extraction will only increase by some 1.8 times. This means that within the time frame from 1975 to 2010, water recycling (recycling rate in Fig. 2) of about 43% in 1975 will increase through 55% in 1995 to over 65% in 2010. Up to now, however, in those regions where natural water reserves are still adequate, water savings measures are very largely confined to the industrial sector, whereas in the municipal sector, the recovery of water by recycling, reuse or perhaps utilization of rain water has been adopted only in a few exceptional cases, or under certain special conditions applying regionally, for instance in the city state of Singapore.

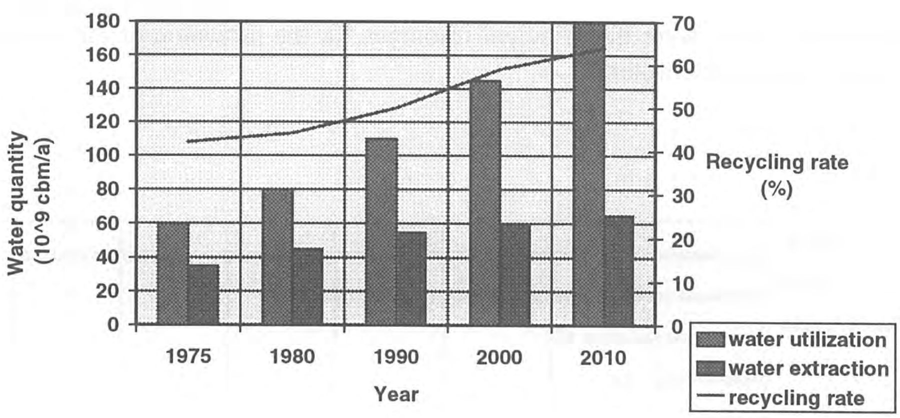


Figure 2. Actual and predicted industrial water demand and extraction in Western Germany

The situation is different in those regions suffering under water deficiency, or where external resources or technology has already to be employed for the preparation of fresh water. Here, the high costs of fresh water production, for example by seawater desalination, have led much earlier to recovery of waste water, in major industrial complexes but also for municipal and domestic use as well as land irrigation. However, also in these countries, in which water is still not a limiting factor for economic growth, the increasing degradation of raw water and ground water quality due to the influence of agriculture and industry, as well as the expanding water demand of the population and of industry have led to a process of rethinking away from the resource water of unlimited availability, to a commodity which has to be considered under quality and cost aspects.

The economic and targeted use of the increasingly valuable water resource can only be achieved by adopting a range of technical and organizational measures. These are:

- optimization of water consumption in line with the specific quality requirements of the consumers
- the reduction of uncontrolled fresh water losses within distribution networks (unaccounted-for water)
- in industry
- product oriented minimization of water consumption
- water recycling and reuse
- use as far as possible of treated municipal sewage (tertiary effluents) for agricultural and municipal irrigation, and its utilization at places of consumption for which not such a high water quality is required.

All these technical measures contain a significant potential for the substainable use of fresh water. Nevertheless, these are not the sole aspect under which a future-oriented water economy has to be considered.

THE URBAN/INDUSTRIAL WATER CYCLE

The increasing interconnections between municipal and industrial water, sewage, waste water and disposal paths result in the arisal of complex water cycles, termed in the following the "urban/industrial water cycle" (Fig. 3).

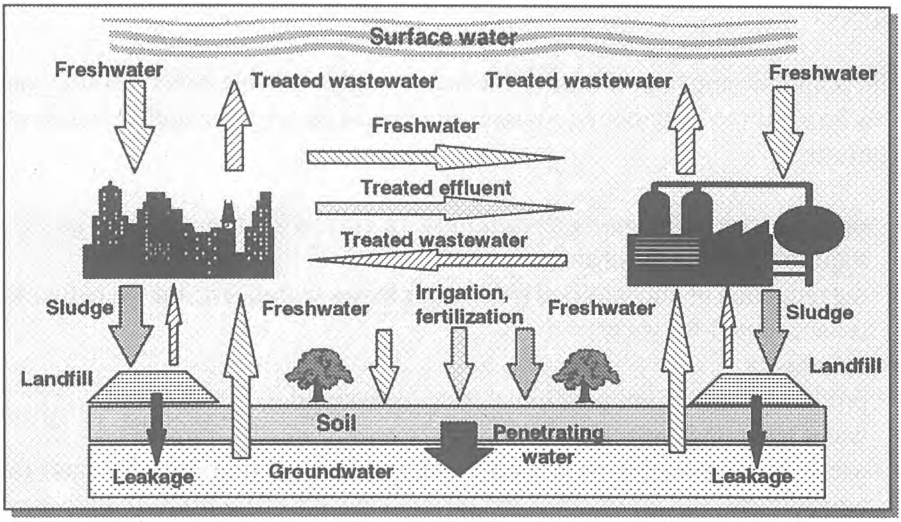


Figure 3. The urban/industrial water cycle

Within this cycle, natural water resources like surface waters, but also in the form of sea water and ground water, as well as land used for agriculture are tied to each other by way of:

- water extraction
- direct discharge of treated waste water and effluent from industry and communities
- piping of treated waste water into municipal sewage treatment works
- utilization of the treated effluent from these sewage works for irrigation
- utilization of the sewage sludge for fertilization
- dumping of sludge from industry and communities

through a multiplicity of intermeshed influences.

Each of these effects are to be considered in more detail in the following.

WASTE WATER SEGREGATION, WASTE WATER RECYCLING AND ITS REUSE IN INDUSTRY

Industrial production and process lines as well as the associated supply installations require services and process water of very differing qualities. Quality ranges from ultra-pure water, demineralized water, water to drinking water standards (particularly in the foodstuffs and beverages industry) by way of partially demineralized and solvent water, down to low quality needs, for which even a certain enrichment of pollutants and an increased salt content may be tolerated. The subdivision of this range into quality stages is not only specific for industrial sectors, but may even differ within a single place of production (Fig. 4).

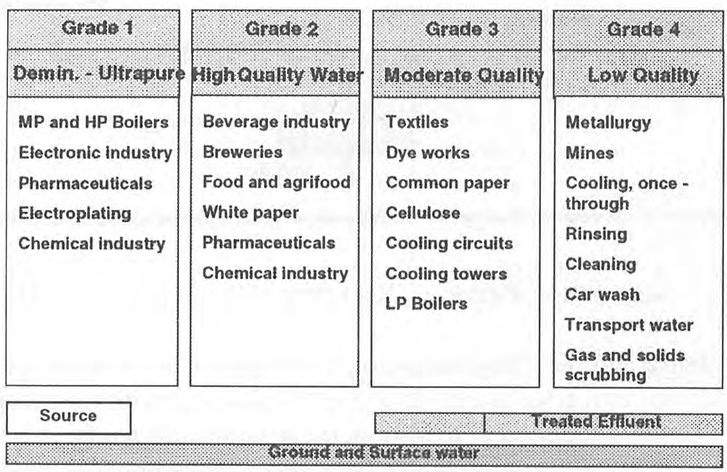


Figure 4. Industrial Water Quality Demand

By appropriate segregation and organization of fresh water applications, and possibly following its pre-treatment in those process lines requiring a high quality standard, and by splitting the waste water generated there into waters which may be reused:

- directly in further process lines
- following pre-treatment
- following more extensive treatment:

It is possible to substantially reduce the requirement for fresh water of a place of production. Due to evaporation losses and concentration of contents at individual usage locations, as also due to the treatment processes, however, inevitably the constitutents of the waste water will become more and more concentrated, so that finally concentrates are obtained which prior to their discharge have to be cleaned in a special waste water treatment step (Fig. 5).

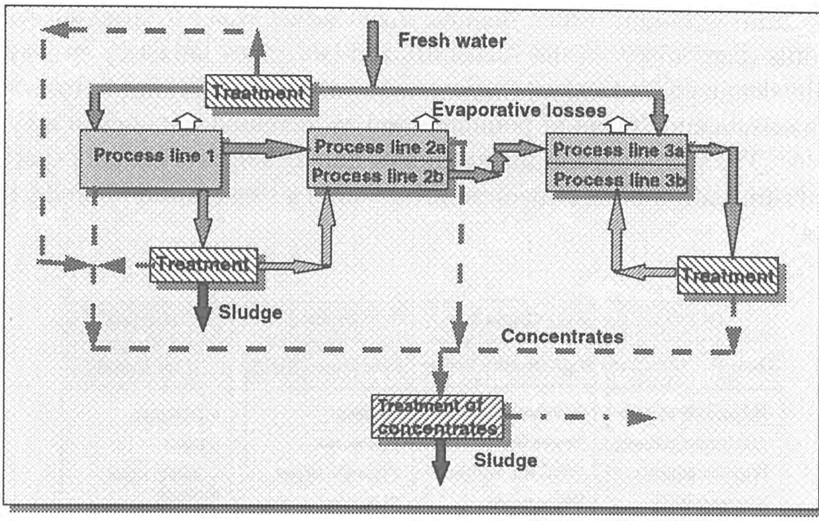


Figure 5. Segregation, Reuse and Recycling of Water in Industrial Processes

For such reuse and recycling technologies a wide range of water and waste water treatment processes is available (Fig. 6), although with the exception of biological processes, chemical oxidation, incineration and pyrolysis these have the effect of splitting the waste water flow into a concentrated solution and a less polluted side stream. In part, treatment additionally concentrates the salts, for example in the application of ion exchange as well as of precipitation and flocculation. Although overall a reduction of fresh water consumption is achieved by means of these industrial water savings measures, in the majority of cases this results in the discharge of effluent which has largely been freed of pollutants but has an enhanced salt content, either to the municipal sewer system or to surface waters.

Principle of Process	Type of Process	Influence on Pollutants: Enrichment	Influence on Pollutants: Degradation / Conversion
Biological Treatment	- Anaerobic		●
	- Aerobic		●
Chemical - Physical Treatment	- Precipitation - Flocculation - Filtration - Sedimentation - Flotation - Stripping	●	
	- Oxidation		●
Adsorption	- Activated Carbon - Special Adsorb.	●	
Ion Exchange			
Membrane Processes	- Ultrafiltration - Reverse Osmosis - Electrodialysis	●	
Extraction			
	- Evapor.,Destill	●	
	- Incineration, Pyrol.		●

Figure 6. Treatment Processes for Waste Water

When considering the capital costs and total costs of such water savings measures in industry, an example from the chemical industry illustrates that with increasing degree of recycling and water reuse, and for a cost minimum at a rate of 70 to 75% recovery, then for furthergoing closing of the water cycles the total costs increase very rapidly at an exponential rate by a factor of 3 (for 98% reuse of the water) in comparison to the cost minimum (Fig. 7). A way out of this cost dilemma could, for example, consist in reducing the consumption of fresh water in industry not by furthergoing closure of water circuits, but instead to make available inexpensively prepared municipal sewage for utilization as service water for consumers with low quality requirements.

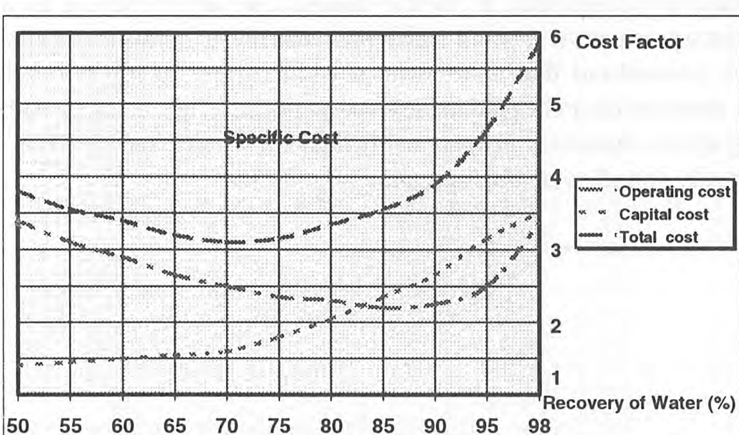


Figure 7. Development of Cost in Industrial Water Reuse

The rise of the proportion of industrial waste water in a municipal sewage disposal system can therefore appreciably increase the salt content of the sewage to be treated, and also be the cause for the ingress of heavy metals into the sewage works, and thus the enrichment of these heavy metals in the sewage sludge.

APPLICATION OF SEWAGE EFFLUENTS FOR IRRIGATION AND USE OF THE SEWAGE SLUDGE IN AGRICULTURE

For discharge of sewage effluents to surface water, the limit values for residual organic pollution as well as for heavy metal contents and organic trace substances as specified in environmental protection regulations have to be complied with. If, however, this effluent, following further treatment, is used for irrigation, additional requirements for the salt content expressed as TDS or conductivity, but also recommended values for the composition, that is the ratio of sodium to hardening constituents (SAR or sodium absorption ratio) must be observed, and also depending on type of irrigation and crops, limits for pollution with micro-organisms and spores.

In countries with a high rainfall frequency and in regions and communities with comparatively small industrial sectors, these irrigation requirements can be met essentially by filtration of the treatment plant effluent and by disinfection. More problematic is its use in regions where sewage has a higher salt content, like in the arid regions of the Arabian Gulf, where even today without a high degree of industrialization salt content and the SAR index are at the limits of the irrigation stipulations. In order to ensure the quality of the treated effluent needed for irrigation, additional treatment measures (Fig. 8) are then necessary, ranging up to membrane processes such as reverse osmosis and nanofiltration, as well as the necessary pre-treatment chain which precedes these. In this connection, it is also to be pointed out that apart from a wide variety of micro-organisms, particular attention has to be paid to the kriptoperiodia. When using conventional sterilizing agents, these exhibit appreciably higher resistance rates, and are viable over a lengthy period even after spreading onto fields.

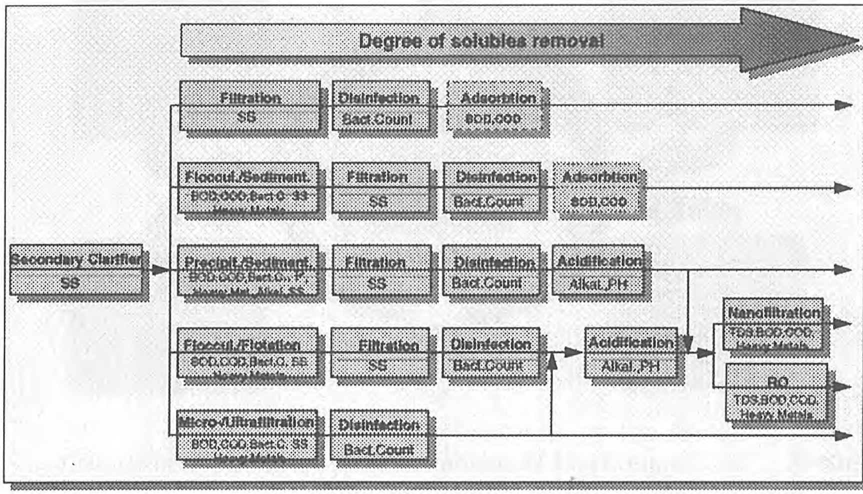


Figure 8. Methods for Tertiary Cleaning of Municipal Effluents

MONITORING AND MANAGEMENT OF THE INTERLINKED INFLUENCES IN THE "URBAN/INDUSTRIAL CYCLE"

Savings in fresh water use by the reuse of waste water both in the industrial and the municipal sectors can be attained by applying a range of effective technical measures. However, the interlinking of these measures within the overall systen of the urban/industrial cycle results in interactions which, particularly in arid regions due to the lack of fresh water input from rainfall and the unavoidable necessity for more intensive utilization of sewage effluents, can be much more problematic in its effects than in the Earth's regions with frequent rainfall. Hence these technical measures should be supplemented by management and organization systems providing a comprehensive picture of the actual situation to provide a basis for determining the influences of future development and the specific changes which then become necessary. Such information and management systems within the urban/industrial cycle are (Fig. 9):

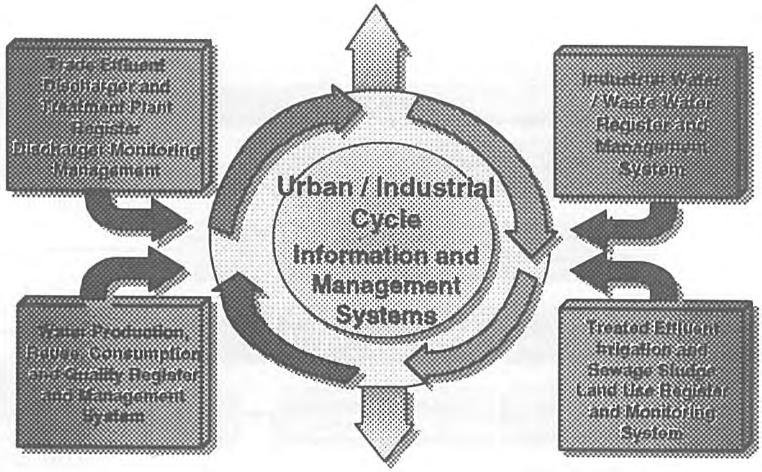


Figure 9. Information and Management Systems Urban/Industrial Cycle

- In the industrial sector, the "industrial water/waste water register and management system" for setting up and organizing works-internal measures for waste water segregation, its reuse and recycling, and representation of the actual status of fresh water consumption and discharged waste water quantity and quality;

- The "trade effluent, discharger and treatment plant register" with a "discharger monitoring management" system to cover industrial discharge with its specific waste water constitutents, compliance with statutory requirements, the organization, cycles of monitoring, and recording of the results of monitoring;

- A "water production, reuse, consumption and quality register with management system", in which fresh water production, extraction quantities, flows of treated effluent stating which rates of flow are sent to which consumer structures, drinking water quality, quality of reused waste water, and ratio of drinking water input to billable consumer flows, can be recorded and organized.

- A "treated effluent irrigation and sewage sludge land use register" in which the plots with their type of cultivation as well the applied quality and quantity of sewage sludge and irrigation water, stating in each case the composition and current soil values (heavy metals and organic trace substances) are recorded, and the corresponding cycles of monitoring and its results are registered.

Depending on the existing organizational structures, such management modules may be used together to make up integrated systems in municipal, industrial and also in higher-level applications.

As an example of such an urban-industrial cycle information and management system, a brief description shall be given of the UBIS Environmental and Operating Data Information Software. By applying this software system, many of the above conditions can be put into practice. Additionally, by means of a link-up with geographical information systems, and in connection with other computerized systems, such as billing systems, the connection of further databanks, such as laboratory information systems, and output of data in standard software packages, this information system will guarantee optimum fulfillment of many of the additional requirements.

The UBIS module for registering dischargers of industrial waste water to sewers, permits, for example, the collection and administration of data on works premises and sections of these, with all associated data for water supply and waste water production.

Fig. 10 shows the waste water discharger screen of this module. Apart from the information shown there, further information, for example as shown in Fig. 11, can be collected and administered. Furthermore, for monitoring dischargers either at the place of waste water production in the works or of companies connected to a sewer network, and by using the integrated software sections "Limit Values" and "Laboratory", it is possible to plan and administer a monitoring and sampling programme, with time schedule and personnel deployment, as well as types and numbers of analyses.

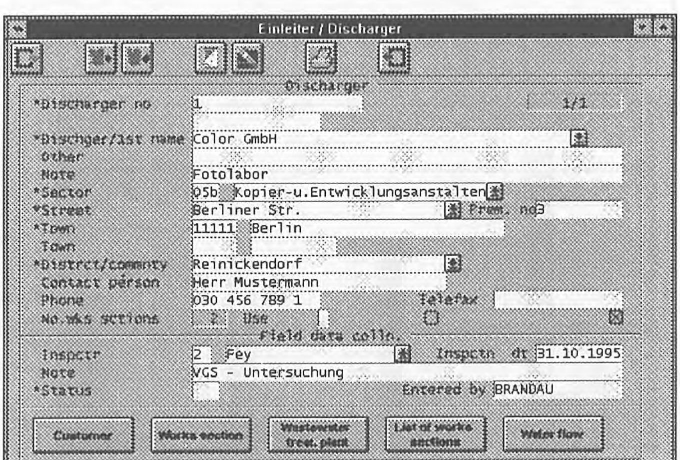


Figure 10. UBIS-Waste Water Discharger Screen

Apart from standardized evaluations, such as:

- violation of limits
- industrial sector statistics
- tracking of substances

the user's own evaluations may be generated by way of search screens.

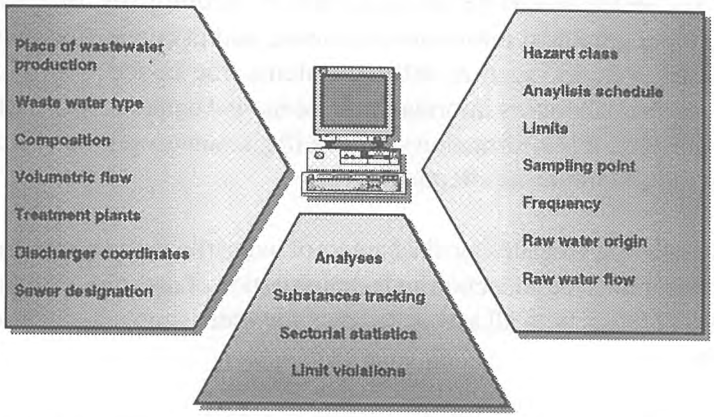


Figure 11: Industrial water/waste water management input and outputs

Also available as a further module is a register of plants, using which data on waste water treatment plants can be collected and administered. Overall, the application of the UBIS software has proven itself in numerous works and in the municipal sector in towns and cities of between 50,000 and 3.5 million inhabitants.

From Fig. 12, taking as an example the heavy metal content in sewage sludge in Germany, it can be seen that a marked reduction has been brought about by appropriate statutory regulations and monitoring of waste water dischargers.

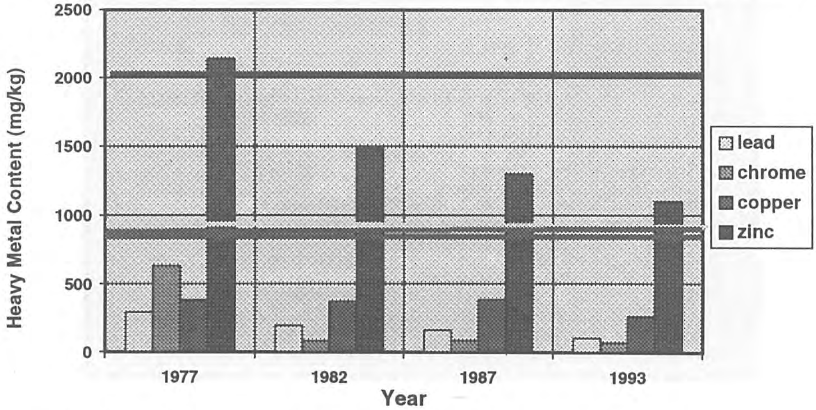


Figure 12. Development of Heavy Metal Content in German Sewage Sludge

Specific Privatization Issues Applicable to Water and Electricity Utilities in the Gulf Cooperation Council States

Jamil S.K. Al-Alawi

SPECIFIC PRIVATIZATION ISSUES APPLICABLE TO WATER AND ELECTRICITY UTILITIES IN THE GULF CO-OPERATION COUNCIL STATES

Jamil S. K. Al-Alawi
Business Promotion Center, Bahrain

ABSTRACT

Most of the GCC States have attempted the path of privatization in recent years in order to relieve the financial burdens of capital expenditure from the government. A sudden rush towards privatization has resulted in unfortunate obstacles to most of the proposed privatization of utilities projects in the GCC States. The paper deals with specific economic, political and social issues that impact on the administrative and financial style of management in the GCC States which in turn has reflected on the performance and cost to the government and the public, as compared to utilities management elsewhere in the developed countries. A review of the forces which drive the GCC governments to the privatization process that took place and the obstacles which have hindered the progress towards successful privatization, with alternatives, in order to achieve the privatization goals and a high standard of service to the community at the least cost in order to support the economic and social development of the GCC States. Suggestions of steps towards privatization process with a prerequisite that ensure its success are also presented. The review also identifies some examples of successful and efficient independent authorities, with a comparison of the various types of utilities management, i.e. government, independent authority and private company showing the strength and weakness of each type. The social and the political implications as a result of the privatization process are also been identified, with a particular emphasis on the tariffs and employees. The issue of ownership and funding of water and electricity utilities has been reviewed as being a very important commodities that affects the economic and social development of the country. Suggested recommendation is given towards balancing the risks if a decision is made to proceed with privatization projects. The paper concludes that successful privatization will depend on the ability of achieving a better customer services and creating a base of highly trained productive employees and delivering the products at lower cost than existing government or independent authority.

BACKGROUND TO UTILITIES OWNERSHIP WORLDWIDE

Governments and public all over the world have always looked at water services as an available natural resource which should be provided by the government as a free service or at the least cost. Meanwhile, other services such as electricity, gas, and telecommunications whether provided by the government or by private companies have always been expected to be charged.

The ownership of such utilities has been dependent on the political or economical conditions that existed from time to time. Almost all water companies were, until the 1980's, owned by government.

The Privatization process of electricity was initiated in the United States of America in the seventies, due to the sudden increase of oil prices and the drive for more efficient plants and the lack of Government funds to invest at that time. This process was followed by Conservative British Governments in the early eighties with the objectives of reducing national debt; increasing efficiency and establishing competitive markets for utilities. Other public utilities have followed this pattern in the United States and the UK.

The end results of Privatization differ from place to place. In some countries the objectives have been achieved, whereas in others they have not. In Britain the cost of these utilities have risen very sharply, mainly due to the large dividends paid to shareholders and the exorbitant salaries and bonuses paid to executives. Poor service to customers has resulted from the major cuts in staff numbers employed, and was widely criticized in the UK.

Elsewhere in Europe and other parts of the world, Privatization of utilities has taken a longer period of time and more careful consideration. The threat of Privatization has been sufficient for utilities in all countries to improve efficiency and reduce staff numbers.

The success of Privatization in the developed countries was due to the existence of well developed capital markets and availability of sufficient private funds to absorb the share offerings.

BACKGROUND TO UTILITIES OWNERSHIP IN THE GCC STATES

The history of the GCC States utilities ownership is not different than the rest of the world, which have all gone through the private and state owned stages.

The present status of water and electricity utilities are as follows:

- Kuwait, Bahrain, Qatar and UAE (except Dubai) are fully government managed and owned.
- Saudi Arabia is a mixture of government owned authorities and private electricity companies with the government as the majority shareholder.
- Dubai in UAE has established a company for water and electricity.
- Oman has in 1995 awarded a contract for water and electricity station on a BOT basis. Utilities are government owned and managed.

GENERAL REVIEW OF RECENT PRIVATIZATION IN THE GCC STATES

Most of the GCC States have attempted the path of privatization in recent years in order to:

- Relieve the financial burdens of capital expenditure from the government.
- Create a vigorous and expanding private sector.
- Stimulate the national economy by adopting privatization of existing entities as a quick and easy solution.

A sudden rush towards privatization has resulted in unfortunate obstacles to most of the proposed privatization of utilities projects in the GCC.

Some of the reasons attributed to these obstacles are:

1. Not enough thought and preparation have been made by the governments in defining their long term objectives of privatization.

2. International consultants and developers tried to impose privatization structures that worked elsewhere in the world, but were not suitable for the GCC States.

3. High levels of subsidies for water and electricity.

4. Absence of real competition has resulted in very high unit costs proposed by developers of independent electricity & water projects.

5. The size of the utilities does not justify fragmentation of production transmission and distribution with a number of developers operating systems in parallel to existing utility.

6. Scarcity of water in this area of the world, and the requirement for desalination process dictate the need for a combined planning and operation of water and electricity utilities in order to maximize efficiency and reduce overheads.

7. Unique local problems such as legislation, risks, lack of local knowledge etc.

Major similar Independent Power Plant (IPP) schemes in various developing countries are being reconsidered, due to similar reasons.

SUGGESTED STEPS TOWARDS FULL PRIVATIZATION IN THE GCC STATES

The present status of all utilities in the GCC States reflects a domination of government decisions irrespective of the type of management and ownership. This situation has led to inefficient operations, poor management and uncontrolled growth in demand due to very high levels of subsidies.

If a decision is to be made towards privatization then the government should always consider the total system of production, transmission and distribution of combined water and electricity organizations in order to avoid high overheads and efficient utilization of high capital plant and fuel. In some cases, such as Saudi Arabia, privatization of production and transmission alone can be justified. Meanwhile, the size of the systems in the other GCC States, cannot support many utilities running small independent power plants (IPP).

The other issues to be considered include the need to improve the performance of the organization and gradual restructuring of the tariff before embarking on privatization.

Finally the most import requirement is to develop highly liquid capital markets to manage and absorb substantial share offerings.

In order to avoid abuse by private monopolies and to transfer the maximum benefits from privatization to the customers, the governments would need to:

- establish a sound system of regulation to monitor tariff charges and performance.
- agree an adequate rate of return on capital to attract new capital for a continuously expanding system, while meeting government's overall financial and other objectives.

As shown from the experience of the industrialized countries when they implemented privatization, whilst the above prerequisites cannot be achieved quickly or easily. It is not a quick process, this does not mean that it cannot be done. Privatization can be implemented in stages as follows:

1. The conversion of the existing water and electricity organization to an independent government owned authority, who would take over 100 % of the assets.

2. The Authority should be given all the necessary resources and well defined objectives in order to establish a sound management structure, and put in place a good accounting system, which can provide proper commercial profit and loss accounts on a timely and regular basis.

3. The government should establish a clear financial relationship by not subsidizing any services to the Authority. At the same time the Government must enter into a clear agreement with the Authority to cover the cost of subsidies to the public, in order that the Authority can be put in a healthy financial situation.

4. The Authority should propose to the Government to restructure the tariffs, without an immediate significant impact on customers, in order to control and manage growth in demand.

5. The Authority should develop a comprehensive 10 year business plan, giving details of all capital & revenue expenditures with projections of all costs and

incomes. The plan should include realistic targets for improvements in efficiencies per sector; staff training and early retirement benefits as well as long term proposals in order to eliminate direct subsidies.

6. The Authority should be fully independent; raise its own moneys; reward its own staff for extra efforts and results; and be responsible for improving efficiency and reducing costs while at the same time providing better customer service.

7. The Authority should work on the basis that the cost per unit delivered to its customers shall not exceed the equivalent economic cost prior to its establishment.

After a few years of successful operation of the Authority when all the privatization prerequisites have been achieved, it is only then that the local private sector should be invited to take up shares gradually at a rate which the market can absorb.

In most cases full privatization of generation, transmission and distribution is not the ideal solution. Therefore, the establishment of an Authority could be a better solution. This is especially true if it is managed properly, and the Authority's results match those of a private company.

FORMS OF MANAGEMENT STRUCTURE FOR UTILITIES

The following comparison illustrates the differences between the various forms of management discussed in this paper.

- Government management.
- Independently managed Government Authority.
- Private company management.

Comparison Between Forms of Utilities Management Structure

Factors	Government	Authority	Private
Political and Social Influence	Major	Partial	Minimum
Efficiency	Low	Medium/High	High
Labor Policy	Inflexible	Flexible	Flexible
Salaries and Benefits	Inflexible	Flexible	Flexible
Availability of Funds for Investments	Restricted	Unrestricted	Unrestricted
Government Guarantees	Full	Not required	Not required
Contribution to Economical activities	Partial	Partial	Full
Tariff Adjustments	Restricted	Unrestricted	Unrestricted
Accounting System	Government	Commercial	Commercial

As it can be seen from the above comparison that the independent authority form of management shares most of the above factors with the private company except for two, the political and social influence and the contribution to the economical activities of the state which is a matter of government policy.

FORCES WHICH DRIVE PRIVATIZATION

Privatization in different countries can be driven by a combination of political and financial reasons. The benefits of privatization as seen by all governments are a mixture of the following factors :

- Companies in the private sector do not require government guarantees when borrowing to finance the capital programs, and are not constrained by the government's budget limitations.

- Private utilities companies are run on the basis of efficiency, therefore, the unit cost would be cheaper than that from government owned utilities.

- The listing of Utility companies presence in the stock exchange increases the economical activities of the country by promoting the development of capital markets, and the spread of share ownership.

- The sale of government owned assets in a utility allows the government to utilize the money in other needed projects and reduce the financial burden, particularly in a period of low oil revenues and very high level of expenditure in water and electricity sector.

SOME EXAMPLES OF EFFICIENT SUCCESSFUL PUBLIC UTILITIES

These are some examples of very successful Utilities, providing high level efficient services to their customers.

- Tunisia Electricity & Gas Authority
- Tunisia Water Authority
- Jordan Electricity Authority
- Jordan Water Authority
- Singapore Public Utilities Board (PUB)

The Jordanian Government has decided to gradually privatize the electricity sector by converting the Authority to a Company jointly owned by the Government and the private sector.

PUB covers electricity, water and gas supplies in Singapore, and is acknowledged to be highly efficient in operations, and provides excellent levels of customer care. It is financially sound, receives no government subsidies, and is totally independent in raising money for capital development and in making management appointments.

PUB is a model of the high efficiencies which can be achieved by a government owned utility, if it is given the appropriate working relationship with the government and the freedom to act commercially. Such a model could be an ideal model for the GCC States to follow.

SOCIAL AND POLITICAL IMPLICATIONS OF PRIVATIZATION

The sensitivity to privatization varies from one country to another, and is also dependent on the economic and social structure of the country.

Water and electricity utilities are looked at by the government and public as important services due to the vital needs of their products, which no one could survive now a day without. Therefore, the public opinion in the GCC States feels that such utilities should either be monopolized by the government or owned by an open public company, and not be foreign owned.

The measure of success of any fully privatized utility will be dependent on the following factors:

- Tariff → Has to be ***cheaper*** than the existing utility.
- Cost per unit → Has to be ***lower*** than the existing utility.
- Government subsidy → Has to be ***lower*** than the existing utility.
- Quality of the service → Has to be ***better*** than the existing utility.
- Employees → Have to be ***better*** trained and paid than the existing utility.

If any of these factors are not achieved, then the question will be raised *"Why should we change from a government monopoly to a private monopoly"*.

a. Tariffs implications

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 dependent on the political, social and the economical status of each government.

Providing adequate supply of water and electricity services with the challenge of the uncontrolled annual demand, in an industry that requires substantial investment and high operating cost, has created major financial difficulties for all the GCC States 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 policies and put in place higher tariffs before any attempt is made to consider privatization.

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

Direct subsidies in some GCC States are as high as 80% of the costs.
The indirect subsidies are a combination of :

- Gas and oil being supplied at prices much below world market prices.
- No interest charges made for money used on capital projects.
- Free or nominal charges for services from other Government Agencies.

Unfortunately Subsidies are generally given to all customers, even those with a high level of disposable money and who individually use very large quantities of water & electricity. As a result the wealthy customers receive the highest financial support in the form of subsidies.

It is suggested that new forms of subsidy structure be considered by all governments in the GCC States. This new structure should allow the utility to be in direct relationship with all consumers who will be charged the full economical cost of the water & electricity services provided. The government should in turn through the social welfare system pay only the needy consumers a fixed annual sum.

By adopting this method the government will achieve:

- Reduction in level of subsidy.
- The subsidy will be directed only to those who need it, and wealthy consumers will pay full cost.
- Conservation drive will be more effective.
- The annual demand growth will be manageable.

b. Employees implications

Transformation of water and electricity utilities to an independent authority or fully privatized organization will not cause a problem for security of employment of existing employees for the following reasons :

1. Water and electricity demand is directly related to economic and population growth. The population in the GCC States is growing at an average rate of 3% per year. To meet this increase in demand requires a continuous additions of a new plants and networks which in turn will require additional staff to manage and operate them.

2. Except in Bahrain, where 90% of the employees are Bahraini nationals, other GCC states employ a large number of expatriates, who will gradually be replaced by locals as fast as they are available for training.

3. There is no substantial local over staffing in GCC states utilities, and the cost of such over staffing is very small.

4. By adopting proper training programs to improve productivity coupled with incentives and earlier retirement for the untrainable staff, the implications on local staff should be minimal.

OWNERSHIP AND FUNDING OF WATER AND ELECTRICITY UTILITIES

There are special considerations, which must be taken into account, when decisions are made about ownership and funding of utilities :

- Water and electricity utilities are considered by the public as more fundamental and essential for living than other utilities such as communications and gas, whose services can be owned by the private sector.

- People are convinced that the government must either own or strictly control the regulations for water and electricity utilities. In the UK the former Prime Minister Harold Macmillan opposed privatization of utilities and described it in the House of Lords as *"like selling off the family silver instead of passing it on intact to the next generation"*.

- If the utilities are privatized then it is essential that equity shares must be owned locally, and must not be totally in foreign ownership.

- Funds and financial institutions, such as Gulf Investment Corporation and pension funds, are available in the GCC States to lead the way in taking equity shares in utilities. Employees and customers should be encouraged to invest in them.

BALANCING THE RISKS IN FULL PRIVATIZATION PROJECTS

The previous sections of the paper have suggested alternatives to full privatization. There is a need to examine what steps and precautions a government should take if it decides to go for full privatization.

The following are some recommendations on how to equitably balance the risks between the government and the developer:

- The government must first study the nature of risks involved affecting both parties, and how those risks could fairly be allocated in conformity with government objectives, and with established industry practice.

- Determine the levels of return on equity that are acceptable long term to both government and investors.

- Understand the need for absolute transparent procedures when inviting proposals, and evaluating them.

- Ensure that the subsequent operating environment, including risk allocation, is clear before starting.

- Accept that the project will only be successful if the risks and returns to both government and investors are properly balanced and fair.

- Realize the difficulty of converting the broad agreement on major legal issues into mutually acceptable wording for inclusion in agreements.

- The overall costs of the water and or electricity produced by a developer must be of the same order or less than that produced by the government.

CONCLUSIONS

1. The alternatives to full Privatization, including the establishment of an independent owned government authority should be evaluated.

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

3. Gradual move towards full privatization after careful preparation of all prerequisites is the key for successful results.

4. Equity investment in privatization should be offered in phases to citizens and institutions within the GCC States economy, and with the least foreign investment.

5. There must be an equitable balance of risks between the government and the developer.

6. The problems of high subsidies in GCC States must first be tackled.

7. Unique local problems must be identified and solutions found for them. Appropriate structures must be put in place.

8. Local staff with management potential must be identified, trained and given the necessary exposure to similar type jobs.

9. Finally to be considered successful, a Privatization Scheme must meet the following objectives relative to the existing utility:

   - Tariff has to be ***cheaper*** than the existing utility.
   - Delivered cost per unit must be ***lower***.
   - Overall Government Subsidies must be ***lower***.
   - Customer Service must be ***better***.
   - Employees must be ***better*** trained and paid.

The Role of Scientific Research in the Development of Water Resources in Saudi Arabia

Ahmed M. Alabdulkader, Abdulrahman I. Alabdulalli and Ali A. Chammam

THE ROLE OF SCIENTIFIC RESEARCH IN THE DEVELOPMENT OF WATER RESOURCES IN SAUDI ARABIA

Ahmed M. Alabdulkader, Abdulrahman I. Alabdulalli, Ali A. Chammam
GDRGP-KACST
Riyadh, Saudi Arabia

ABSTRACT

In arid countries like Saudi Arabia, water resources are the most prominent natural resource because of their scarcity both in quantity and quality. Saudi government has realized the vital role of water resources in the national development processes and thus the importance of using water rationally and efficiently. The scientific research directed to solve development issues in the various national sectors is a key factor for the successful development processes at the national and sectoral levels. The role of scientific research has been directed mainly for issues of high priority in Saudi Arabia, at the top of all is the issue of water resources and its development of water resources in Saudi Arabia, with emphasis on research projects funded by King Abdulaziz City for Science and Technology (KACST), and called for a fruitful cooperation and coordination among the various national research centers in one side and between the national research centers and the respective governmental agencies on the other side to avoid redundancy in research and to benefit society from the findings of such efforts. The paper, also, suggested some of the research topics priorities concerning the water issues in Saudi Arabia.

OVERVIEW OF WATER IMPORT BY SEA AS AN ALTERNATIVE SOLUTION TO THE MIDDLE EAST WATER SHORTAGES

Marwan Haddad[1], Anan Jayyousi[2], and Numan Mizyed[3]
[1] Water and Environmental Studies Center
[2] Civil Engineering Dept., College of Engineering
[3] Department of Plant Production, College of Agriculture
An-Najah National University, P.O. Box 7, Nablus, Palestine

ABSTRACT

Water import by sea is a feasible alternative that can be used to bridge the increasing gap between water supply and demand in the Middle East. Two main methods of water import by sea were evaluated: import using tankers and import using bags. While water import using tankers is more realistic from technical point of view, bags for the time being still in the development and testing phase. The cost of water imports is ranging from 0.49 to 1.01 $/m^3$ using old tankers, and 0.60 to 1.36 $/m^3$ using new tankers, and 0.41 to 0.68 $/m^3$ using bags. The study marked many environmental and socio-economic remedies that will be gained from importing water by sea. However, clear regional agreements with international guarantees and strong organizational and enforcement structures and mechanisms are essentials for the process to be sustainable.

INTRODUCTION

Demands for water in the Middle East (ME) is increasing as a result of the rapid population growth and socio-economic development. Taking into account the limited amounts of available water supply in the region, water shortages are increasing. This requires evaluating all possible options to close the water gaps. One of these options is to import water from areas rich in water sources.

A wide variety of techniques and methods were used to transport water from sources to demand points. Two main components should be considered in water transport: the source of water and the method of transportation [1].

Water transport from the north to the south of the ME has been done naturally through the Euphrates and the Tigris. Those two rivers originate in Turkey from which they transport large amounts of fresh water to the arid land areas in southern Syria and Iraq. This water was responsible for originating some of the earliest civilizations in history. Although the demands for such water have been increasing in the arid south, the amounts of water flowing through these two rivers are reduced and expected to reduce in the future. This situation might reduce the role of these two rivers in the economy of the region and calls for new methods of transportation especially for those areas that those rivers can't reach.

As natural transport of water to the arid south is not able to reach all countries of the region, there is a high concern of moving water artificially to demanding countries.

When someone looks at the ME and the Mediterranean region will realize that the Mediterranean sea is dividing two sides with extreme differences in water availability. Therefore, it would come to one's mind the idea of transporting water across the Mediterranean as an attractive option as it has been the main method for transporting oil in the other direction. Two possible options of moving water may be considered: transporting water by land and by sea. This paper is exclusively concerned about the transport of water by sea.

This paper presents and discusses water import by sea including potential water sources available for import, the technical aspects of water import by bags and by tankers, legal-political-economical-financial and environmental factors affecting the sustainability of the process, and the organizational structure for managing such process.

POTENTIAL WATER SOURCES

Regardless of all factors that affect water import from a certain source, several potential sources are available to import water to the region. The annual internal renewable water resources and the demand for different countries that might be a good potential source of water imports were presented in **Table 1**.

As shown in **Table 1**, the Mediterranean divides two zones with high variability in water availability. To the south and east of the Mediterranean is an area with high aridity and severe water shortages. However, to the north of the Mediterranean Sea, is an area which is humid and very rich in fresh water sources.

Taking into consideration that the estimated fresh water gap for Jordan, Israel, and Palestine until the year 2040 is about 3 km^3 (WESC 1995), it is possibile from quantitative point of view to transport water from the water rich areas in the north of the Mediterranean to the areas poor in water in the ME.

TECHNICAL ASPECTS OF IMPORTS

To study the technical aspects of water imports by sea, we have to consider the whole process including water diversion systems, water loading and unloading terminals, and water transport methods.

Water Diversion Systems.

Any water diversion will include intake structure and conveyance lines from water source to loading terminals. The description of such systems is site dependent. From a technical point of view, for any river system, appropriate intake and conveyance structures could be designed with an initial capital depending on the amount to be transported and the type of flow. It is possible to use short lines to carry water from the river to the loading points and utilize pumping. However, to reduce the running cost, water could be diverted from a higher point using longer pipes to carry water using gravitational flow.

Table 1. The annual Freshwater Resources and Withdrawals [2]

Demand (Km^3) 1996	Supply(Km^3)	Country
37.7	198.0	France
0.2	21.3	Albania
33.5	193.1	Turkey
153.4	468.0	Pakistan
45.4	117.5	Iran
2.0	392.0	Norway
7.8	90.0	Netherlands
0.8	50.0	Ireland
11.8	71.0	U.K.
56.2	167.0	Italy

Water loading Terminals

Water loading terminals are similar to those used for oil. Thus, their costs and technical description are similar to those for oil. There are several systems for terminals currently used for oil loading and unloading, these include [3]:

A. Artificial harbor protected by concrete jetty and breakwater. This system is very expensive especially in shallow waters.

B. Artificial offshore island made up of steel construction or pre-cast concrete pilings supporting pre-cast or cast-in-places concrete deck structures.

C. Multiple buoys systems consisting of several mooring buoys anchored around a berth. These are less expensive systems and consist of multiple buoys arranged in a semi-circle.

D. Tower mooring system consisting of a steel structure fixed to the bottom by piles.

E. Single point mooring system: The advantages of this system include: tankers could rotate around themselves and loading could be done with waves up to 4.5 meters.

Water Transport Methods

The main water transport methods were considered, transport by bags and transport by tankers.

Transport by bags

Importing water by bags was studied by several companies, but such possibility is still under research and development [4]. The Medusa Corporation of Canada [5], and the Nordic Water Supply of Norway are the companies who seriously invested in the bag technology. In this section we discuss the various components of transport by bags and the latest results of research and development made.

The idea of the bag came to mind several years ago when the Medusa corporation of Canada and Nordic Water Supply noted that there was no water equivalent of the crude oil supertanker. At that time, the supertankers were the cheapest means of moving anything. Water is worth roughly one-thousandth as much as crude oil and quite different technology must be employed to move it. To reduce the cost of its transport per unit, larger and cheaper containers could be utilized. As the environmental impacts of sea accidents between water transporting vehicles are minimal (a fresh water spill is harmless compared to an oil spill), cheaper and less durable transporting methods could be utilized such as bags (flexible bodies).

The technology of the bags has been developing quickly for the last 10 years. Bags up to 10,000 cubic meters have been tested by the Norwegian Nordic Water Company. A bag of 10000 m^3 was tested in January 1995 for one week by Nordic water. That bag was broken after 1.5 days in its second trip last March in North Sea. Nordic Water Company claims that they discovered the cause of failure and they fixed it. They are planning to test the fixed bag next fall in a trip from Norway to Netherlands. After proving successful, a bag with size of 30000 m^3 will be developed and tested which is expected to be done within three years. Nordic water is aiming at developing a commercial bag with a size of 80000 m^3. This size could be feasible for transport of water for long distances in the order of 600 Km. Bags smaller than that size are not economic for long distance. Although the maximum bag developed and tested by Medusa Cooperation is 3000 m^3, but this cooperation has much bigger ambitions. It is looking for funding a research project to test bags of size of 100,000 cubic meters. Such research projects looks pre-mature as long smaller sizes in the order of 10000 m^3 are still under testing. The imaginations of Medusa go much further and think that if the 100000 m^3 are found feasible, then further research and developments are needed for larger bags. As reported, development work to date has involved construction and experimentation with several models in wave and tow tanks [4] as well as a 100 meter long prototype deployed in the ocean north of Vancouver, Canada. This work has established many things such as:

- Optimum shape of the bag
- Static and wave-induced stresses

1. Turkey is close to the Middle East region.
2. There is a terminal under construction in Turkey with the main purpose of water export.

The analysis was performed on a range of imported amount rather than on a single amount. These amount ranges from importing 125 MCM/a to importing 2750 MCM/a. For each alternative three sub-options were investigated. Those are import by bags, import by old tankers, and import by new tankers. More details of the economic and financial analysis of water imports by sea are presented in *Haddad, Jayyousi, and Mizyed,* 1997.

The financial analysis were performed based on the following assumptions:
1. The prices used in this analysis are bas1. ed on the 1996 prices.
2. No royalty cost of water is applied.
3. The useful lifetime of the different projects components is:

Terminals	30 years
Bags	7.5 years
Tugs	15 years
Tankers(22 y. old)	8 years

4. The salvage value of the different project components is zero except for the tankers were the salvage value is taken to be 25% of the initial cost.
5. Three interest rates are considered. those are 0%, 5%, and 10%.
6. A service factor of 80% is assumed.

A summary of the results of the unit cost of water obtained from the financial analysis and the estimated initial cost for each option are presented in Figures 1 and 2 respectively. The figures shows that :

1. The cost of importing one cubic meter of water varies with both the transporting method and the size of the facility.

2. For bags, the cost ranges from 0.68 $\$/m^3$ for a terminal capacity of 125 MCM/a to 0.41 $\$/m^3$ for a terminal capacity of 2750 MCM/a with a 5% interest rate.

3. For old tankers, the cost ranges from 1.01 $\$/m^3$ for a terminal capacity of 125 MCM/a to 0.49 $\$/m^3$ for a terminal capacity of 2750 MCM/a with a 5% interest rate.

4. For new tankers, the cost ranges from 1.38 $\$/m^3$ for a terminal capacity of 125 MCM/a to 0.60 $\$/m^3$ for a terminal capacity of 2750 MCM/a with a 5% interest rate.

5. The initial cost for using new tankers is much higher than the initial cost required for both the bags and the old tankers options.

According to Nordic water, the transport cost ranges from $ 1.9 per cubic meter for a bag size of 30,000 cubic meter to $ 0.65 for a bag size of 160,000 cubic meter. Add to this 7 cents for storage and treatment, and 33 cents on average for terminal cost gives an estimated cost ranges from $ 1.05 to $ 2.30 per cubic meter for bag sizes ranging from 160,000 to 30,000 cubic meter respectively. These numbers are comparable to the numbers obtained in our study keeping in mind that the bag size used in our study is large compared to what was used in the Nordic water estimates (1.6 million cubic meter).

Sustainability of Water Import by Sea

Water supply imported by sea need to be sustainable in time and space and in quality and quantity. Such project can be implemented through direct bilateral relation between the import and export side with some advantages, however it is our belief that better sustainability can be achieved and maintained through a project that serve the region as a whole and not a single entity.

In time means that such large investments in loading and unloading facilities and other structures and means for water transport need to cover a service time of 25-50 years as any other engineering project. Short term supplies (10-15 yrs) are very costly and infeasible unless such project is done in very small scale (40-50 mcm/a).

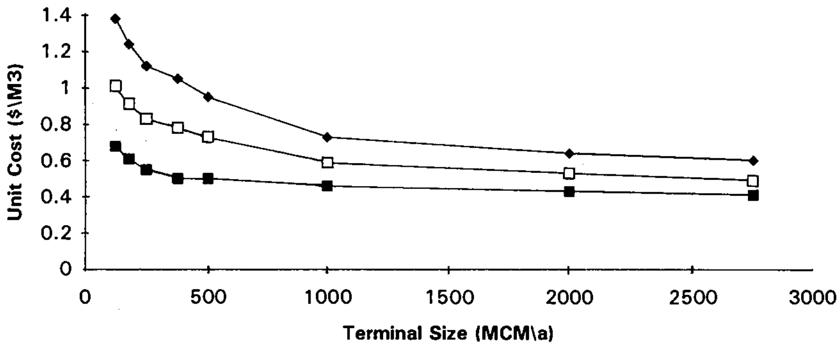
It is expected that a regional project on water transport by sea would be less vulnerable to interruptions. However, because of the political vulnerability in the ME hostile actions and poor crisis management might cause problems. Therefore, sustainability of free access and well operational of the loading and unloading facilities and major conveyance lines and connections is of high importance. This goal can be achieved through a regional agreement(s) supported and guaranteed by the international community and big powers.

The sustainability of supply in quantity and quality depend on the source of supply and the mode of transport. However thorough investigation on the sustainability of the source need to be studied and examined. Such investigations should include the uncertainties regarding of possible future development of the resource by the home country and its effects on the long term qualitative and quantitative sustainability of supplies and the level of commitment that can be given in this regard. Another aspect is that some elements related to water transport by sea, e.g., transport using bags, still in the testing and research phase and information and data collected and available does not represent a sound basis for final decision making and the input of large investments in the sector or option.

It is of important that joint regional water quality standards and rules along with monitoring programs and implementation strategy need to be enforced. Such activities and tasks need a joint management structure or body which will deal with everyday problems as well as crisis, conflicts, and other uncertainties.

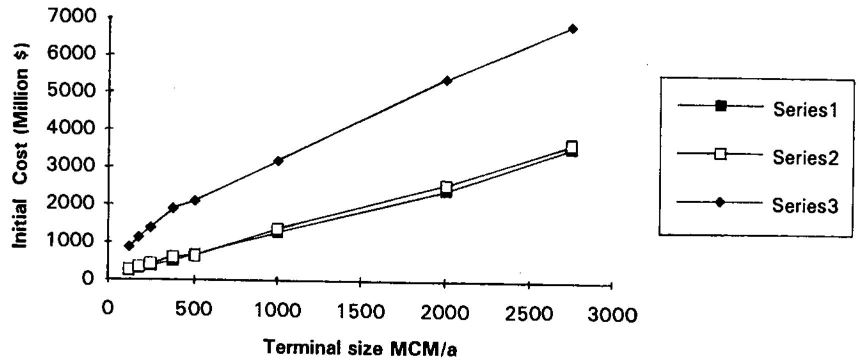
Sustainability of supply require that national water systems be developed to coupe with the quantities of water imported and costs involved. Cooperation between regional parties in using existing national storage and large network facilities in the regional scheme should be carefully tailored

Figure 1 Unit Cost of Water



Series 1: Bags
Series 2: Old Tankers
Series 3: New Tankers

Figure 2 Estimated Initial Cost (Million $)



Series 1: Bags
Series 2: Old Tankers
Series 3: New Tankers

Environmental Aspects

It is expected that on the long run, the introduction of large quantities of fresh water into the region through water transport by sea would lead to a dramatic change in the hydrologic cycle and overall water availability in the region as a whole.

This can be explained that the imported water would be used for domestic purposes only. Assuming that about two thirds of this water can be recovered through wastewater treatment and will be reused in agriculture. Reusing this water in agriculture (grazing, orchards, or restricted irrigated crops) will increase the green cover and food security and reduce soil erosion and aridity.

In addition, it will cause that some of the irrigation water would percolate/drain to the ground water while the rest will evaporate. While the percolation to the ground water will directly enhance its annual recharge capacity, the evaporation of large portion of it will enhance rain intensity which in itself constitute another contribution to the enhancement of water resources availability. Another possible impact is the climatic-temperature and humidity-changes which are directly related to the increase in green coverage and overall water availability.

Environmental aspects related to water import by sea include the effect of imported water on the size and quality of the green coverage, food security and quality of life, aridity and land use, water balance. The change in overall water availability in the region would lead to possible climatic changes, and waste water volumes, composition and treatment.

It should be noted that some of the environmental aspects mentioned above are local/national but others such as rain and water resources enhancement and climatic change are regional in nature.

Organizational Structure

The implementation of a project on water import by sea (WIS) require an organizational management body which will involve local - national, and regional institutions. The establishment of such management structure and its enforcement mechanisms need to be included and detailed in the initial agreement(s) of such project.

The institutional framework of the proposed management organization of WIS (WISMO) should include a board of directors representing all regional parties involved and benefiting from the project along with representatives of donors and funders.

A clear enforcement mechanisms need to be developed and agreed upon. The mandate of such an institution includes the power to establish, coordinate, operate and maintain a system of major storage reservoirs, conveyance lines, pumping stations, loading and unloading facilities, and water transport tankers and/or bags; the power to promote and coordinate studies and work projects for the development of the resource and the transport mechanisms and means; the power to seek and accept grants as well as technical assistance; and the competence to sue and be sued in the courts of the regional parties.

Each party to the project would nominate its representatives to the WISMO board, central and within its area of coverage would establish the local institution(s) needed to carry out the tasks and works in compliance with the central board decisions, directions and procedures.

The decision making process, the location of headquarters and patterns of meetings, and the cost sharing and other responsibities need to be either identified in the agreement or discussed and agreed upon in the first meetings of the central board of directors.

SUMMARY

The following are main summary points drawn out of this study:

1. Two methods of transporting water by sea are investigated. Those are tankers and bags.

2. Several potential sources are available to import water to the region. Turkey was considered because of its close location to the region (675 Km).

3. Based on 5% Internal Rate of Return, the cost of importing water by bags ranges from $0.68 per cubic meter for a quantity of 125 MCM/a to $ 0.41 for a quantity of 2750 MCM/a including transportation, storage, and treatment cost. However, the use of bags is still questionable. Thus, no plans or projects could be based on the use of bags at this stage.

4. Based on 5% Internal Rate of Return, the cost of importing water by old tankers ranges from $ 1.01 per cubic meter for a quantity of 125 MCM/a to $ 0.49 for a quantity of 2750 MCM/a including transportation, storage, and treatment cost. While for new tankers the cost ranges from $ 1.38 to $ 0.6 for the same quantities respectively.

5. The method of tankers of this stage is more reliable because the method of bags is in the research stage at present and further research and development is needed in different areas.

6. Import of water by sea is bringing new conditions and changes to the region most of positive nature.

7. Treatment of water should be done on the demand side to make sure that water quality reaching the consumer is adequate after the transport where water contamination is possible.

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UNESCO's International Hydrological Programme and Sustainable Water Resources Management in the Arab Region

A.M.A. Salih

UNESCO'S INTERNATIONAL HYDROLOGICAL PROGRAMME AND SUSTAINABLE WATER RESOURCES MANAGEMENT IN THE ARAB REGION

A.M.A. Salih
Regional Hydrologist
UNESCO Cairo Office

ABSTRACT

Water availability and scarcity in the Arab region have been reviewed and the most outstanding technological constraints have been identified. The International Hydrological Programme (IHP) of UNESCO has been overviewed and recommended as a regional framework for assisting in establishing sustainable management approach to the scarce water resources of the Arab region.

INTRODUCTION

Sustainable Management of Water resources is a must for survival in the Arab region where water scarcity is becoming a development constraint seriously impeding the economic growth of many countries in the region. Most of these countries are located within arid zones which are known for their scanty annual rainfall, very high rates of evaporation/evapotranspiration and consequently extremely insufficient renewable water resources. The problem has been lately magnified by the vastly expanding population in this century together with the increasing per capita water demand to meet the huge socio-economic developments of the last three decades, especially in the Gulf countries.

The above situation is made even worst by the fact that most of the surface and groundwater resources in the region are, respectively, drawn from shared rivers and aquifers. This fact together with indigenous natural water scarcity have led to the current speculations of severe regional conflicts and high prospects of confrontations. The consequences of water scarcity and conflicts could lead to serious crisis and possible confrontations, if they are not looked at, and dealt with, from a mandatory and equitable sustainable approach. Many options are open for this positive approach where the key-words are; knowledge, communication and cooperation. For that approach to succeed, however, a great deal of understanding, wisdom and support are vitally required from the top decision makers, in the region, who should realize that it is a choice between construction and destruction. Shared resources should be viewed as a catalyst for further communication, cooperation and perhaps ultimately integration of efforts aiming towards sustainable management that values human life. Science and Technology could play a leading role in that direction, while the International Hydrological Programme (IHP) of UNESCO, among others, could be utilized as a suitable international framework for the implementation of a scientifically based regional project. This is specially regional project. This is specially encouraging when one reviews the details of the fifth cycle of the IHP (1996 - 2001) where most of the projects of its eight themes identically cover priority areas of this region.

This paper will hence overview the most outstanding water problems in the region and compare that with the opportunities provided in UNESCO's IHP-V projects.

WATER SCARCITY IN THE ARAB REGION

Inspite of the voluminous reports and papers written by authoritative sources, it is unfortunate that wide range of variations are still found in the numerical values indicating the water budget of the region, its sub-regions and the individual countries. As an example of such variations, Table 1 indicates the numerical values of the total volume of traditional renewable and nonrenewable water resources at the regional level. The maximum variations from the average value range from 44% in the non-renewable case to 15% in the renewable sources. The extents of these variations are, certainly, much higher in going down to the levels of the sub regions and individual countries. However, even if one hypothetically accepts the highest values of renewable regional resource indicated above as correct, the Arab region still currently suffers from a great scarcity in its per capita annual water resources.

Salih (1994) has clearly demonstrated the uneven distribution in the availability of water resources in-between the various regions of the World, indicating that the worldwide lowest per capita availability lies within the Arab Region which, unfortunately, has also the highest rate of worldwide annual per capita reduction in these resources. This critical situation has led to the current speculations of ultimate water conflicts and confrontations in this region. These hastily conclusions are reached, basically through subjective definitions of "scarcity limits", using worldwide yardsticks that are usually based only on conventional renewable water resources.

The available information in the quoted literature has been utilized in table 2 to analyze, in a broad regional manner, the future of per capita renewable water resources. All the numbers of the base year 1990 as well as the indicators for future forecasts are selected, based on the author's judgment, from ALECSO (1992) report on "Detailed Programme for the Preparation of Arab Water Security". A total of ***300 x $10^9 m^3$/year*** for the renewable water resources was utilized based on Khouri (1995), being the most conservative estimate.

Table 1 : ***Range and Variations in the Total Water Resources of the Arab Region***

Reference	***Renewable Water Resources $10^9 m^3$/year***			***Non-renewable Groundwater $10^9 m^3$***
	Surface flow	**Groundwater Recharge**	**Total**	
ROSTAS, 1988	**295**	**41**	**336**	**14215**
Khouri, 1990	**282**	**35**	**317**	**13498**
ALECSO, 1992	**307**	**45**	**352**	**7700**
Saad, 1993	**307**	**40**	**347**	**19573**
Abu Zeid, 1995	**352**	-	-	-
ACSAD, 1994*	**295**	**45**	**340**	-
Khouri, 1995	-	-	**300**	-
POPULATION ACTION INTER., 1995	-	-	**405**	-
Gleick, 1993	-	-	**411**	-
AVERAGE	**306**	**41**	**351**	**13745**
Highest Variation from Average	**15%**	**15%**	**17%**	**44%**

* ***Taken from Khouri, 1995***

Table 2 : Water Budget of the Arab Region up to 2030

Year ***Parameter***	***1990***	***2000***	***2003***	***2010***	***2030***	***Remarks***
Population in millions	226	304	332	408	758	Using a growth rate of 3% per year
Renewable water resources ***$10^9 m^3$/year***	300	300	300	300	300	Using Khouris's (1995) as a conservative value
Water demand ***$10^9 m^3$/year***	200	269	303	362	671	• 1990's base demands was averaged from wide sources in the literature • 1990's demand rate is assumed for other years.
Balance of water budget ***$10^9 m^3$/year***	100	31	-3	-62	-371	• Year 2003 represents the critical period of full utilization of resources.
Per capita water resources ***$10^3 m^3$/year***	1.32	0.99	0.90	0.74	0.40	Year 2000 represents the beginning of scarcity

No doubt, all of the values in table 2 are subject to the same limitations of accuracy mentioned previously and would hence represent only order of magnitudes demonstrating broadly the actual status of the issue. Considering the above limitations and the assumptions in the remarks column, it is obvious that the regional per capita annual water resources of 1.32 thousands meter cube in 1990 is much lower than the average corresponding value for the world, estimated by Serageldin (1995) as 7.40 thousands meter cube. It is also demonstrated in the table that the year 2000 will mark a decline of the per capita's share to less than the internationally assumed scarcity critical limit of 1000 m^3, while by the year 2003 the regional water demand will almost match the available renewable resources. The picture will look more critical if viewed; at the country's level, in considering deterioration in quality, annual supply variations as well as problems related to shared resources. On the positive side, however, are the opportunities provided through non-conventional resources such as desalination and re-use as well as current appreciation of the need for strict demand management policies.

MAJOR WATER PROBLEMS IN THE ARAB REGION

Whatever quantitative definition is given to the lower limit of water scarcity, Salih and Ali (1992) suggested that water scarcity must be viewed as an opportunity rather than a constraint to sustainable development. They argued that when human beings are faced with scarcity they somehow cope with it and come up with ingenious ways of overcoming it. They quoted in that paper numerous admirable coping mechanisms that had been historically developed by the inhabitants of Arabia as well as few contemporary examples from the arid and semi-arid zones of the world.

Currently, three approaches are classically undertaken by professionals to survive the consequences of water scarcity, namely; to strictly but rationally manage the demand for that precious resource, to seek ways and means to preserve and augment the supply, or more preferably to combine the previous two options in an integrated management plan aiming ultimately to sustainable development. Successful applications of these approaches require high level of technological and managerial capabilities that are unfortunately deficient in many of the region's countries. These deficiencies can be felt mostly in the following fields, which have been repeatedly delineated and reported by many intergovernmental regional expert meetings and almost in all of the six regional meetings of the Arab IHP Committees:

- Integrated sustainable water resources management under arid & semi-arid conditions (with special emphasis on resource assessment, demand management, augmentation of supply, conservation, conflict resolution & management, legislation and regulatory frameworks, ... etc.)
- Protection of groundwater and surface water resources against quality deterioration & over abstraction;
- Rainfall Management (with emphasis on Wadi Hydrology, artificial recharge, harvesting techniques,... etc.)
- Capacity building and institutional development;
- Database and information systems;
- Technology adaptation and transfer;
- Public awareness & participation;
- Research and development.

These areas have also been identified, and actions for solving them have been recommended, by many international meetings and programmes including; the Mar Del Plata Action Plan (1977), the Delft Declaration (1991), the Dublin

Statement (1992) and in Agenda 21 of the UNCED (1992) as well as in many other regional and national forums. These topics have also kept, in a way or another, regular appearance in all of the IHD/IHP programmes of UNESCO since 1965 and are currently being considered in its medium term IHP-V projects (1996 - 2001). Prior to that, UNESCO had developed in the fifties a special successful programme devoted specifically to arid zones.

Unfortunately, little or no progress at all has been achieved, in most Arab countries, in these directions which are vital for coping with water scarcity in a sustainable manner. To have positive impact in these areas, genuine regional programmes and action plans are urgently needed through a well coordinated project where national, regional and international professionals and financial resources are well tapped and efficiently utilized. The themes suggested in the current UNESCO-IHP-V (1996 - 2001) could provide an excellent framework for dealing with almost all of these problems. An outline summary of that Programme is therefore given in the next section of this paper.

UNESCO INTERNATIONAL HYDROLOGICAL PROGRAMME (IHP)

Goals and objectives

UNESCO international scientific cooperative programmes in water resources (IHP, and earlier IHD) were established because both the international scientific community and governments have realized that water resources are often one of the primary limiting factors for sustainable socio-economic developments in many regions and countries of the world, and therefore require an internationally co-ordinated programme for their rational management. Thus, the general objective of the IHD, and later the IHP, were set to improve the scientific and technological basis for the development of principal methods and techniques as well as providing the human resources base necessary for the rational development and management of water resources.

The pursuit of this objective has been fundamental to the search for solutions to basic problems related to, among others, lack of reliable water supplies and sanitation, shortage of food and fiber, inadequate supplies of electrical energy, pollution of surface and ground water, erosion and sedimentation, floods, drought and navigation.

Since the inception of the IHD in 1965, and later the IHP in 1975, great progress has been achieved regarding methodologies for water resources and management as well as in capacity building in the water sector. Not withstanding the attained achievements, the general objectives, unfortunately remain valid, but perhaps with some changes in emphasis. The main components of these changes include the current emphasis given to water resources management for sustainable development and the adaptation of hydrological sciences to cope with the anticipated climate change and the preservation of the environment.

IHP structure and implementation

The IHP is planned, executed, coordinated and monitored at global, regional, sub-regional and national levels. This is accomplished through 140 national IHP committees, the 36 members of the Intergovernmental Council (IC) of the IHP and its Bureau, committees, working groups, rapporteurs, secretariat in Paris and six regional hydrologists well distributed in the regions of the world. IHP programmes are generally executed in close cooperation and great harmony with related UNESCO environmental programmes (MAB, IGCP, IOC... etc.), other United Nations specialized organizations (WMO, FAO, WHO, UNEP, IAEA, ESCWA, ...etc.), regional organizations (ACSAD, ALECSO, ...etc.), non-governmental scientific organization (IAHS, IAH, IAHR, IWRA, WASTA... etc.) and research and academic circles. It remains to be mentioned that the finances of the IHP projects are provided through; UNESCO's regular and participation budgets, country's own resources as well as extra-budgetary sources obtained from various funding agencies (UNDP, WB, UNEP, ... etc.)

THE CURRENT IHP-V : HYDROLOGY AND WATER RESOURCES DEVELOPMENT IN A VULNERABLE ENVIRONMENT (1996 - 2001)

Framework and general outline of IHP-V

In general, IHP-V plans to simulate a stronger interrelation between scientific research, application and education. The emphasis should be on environmentally sound integrated water resources planning and management supported by scientifically proven methodologies.

Within these major issues eight themes, given below, have been identified as a support structure for the whole Programme. They cut across different hydrological scales and different climatic regions, but have integrated water management in a vulnerable environmet as a common issue. The proposed themes are seen as cornerstones within which projects could be flexibly implemented. Due to the special importance of water problems in the humid tropics and the arid/semi-arid zones as well as in urban areas, these regions should gain increased attention.

The eight approved themes are :

- Global hydrological and biochemical processes
- Ecohydrological processes in the surfical zone
- Groundwater resources at risk
- Strategies for water resources management in emergency and conflicting situations
- Integrated water resources management in arid and semi-arid zones
- Humid tropics hydrology and water management
- Integrated urban water management
- Transfer of knowledge, information and technology (KIT)

Any of these themes is devided into projects as shown in annex 1.
To avoid a purely hierarchical structure of the IHP-V programme any theme should emphasize both methodological aspects as well as a process for knowledge transfer. All must include interactions in the biotic and abiotic environments as well as in decision-making.

The products should be considered as the outcome of the world-wide efforts of member states, regional and international organizations. UNESCO, while conducting a large number of activities itself, will co-ordinate all IHP related activities through the Intergovernmental Council of IHP regardless of the method of implementation.

IHP IN THE ARAB REGION

The countries of the Arab region did not benefit, so far, from the IHP as it should have, noting its dominant water scarcity and low water expertise. Its modest involvement within the last 30 years, included, among others; convening sixth regional meetings, formation of 14 national IHP Committees and focal points, training of hundreds of professionals & technicians, few research activities and publications and limited number of advisory missions and reports.

The opportunities provided by the projects in the eight themes of IHP-V could compensate for that and present a sound framework for addressing the eight regional deficiencies indicated previously in this paper. This has been recognized by the participants of the sixth IHP regional meeting, held by the end of 1995 in Jordan where themes 3, 4, 5, 7 and 8 were identified and recommended as identical match to the priorities of the region.

UNESCO Cairo Office (ROSTAS)

ROSTAS programmes in Hydrology are closely co-ordinated with IHP themes and implementation strategies. Hence, many benefits have been gained from UNESCO's IHP training programmes and publications over the last thirty years. However, Cairo's activities for the biennials 1994/95 and 1996/97 have been planned and implemented through four classes of involvement;

- Regular programme activities
- Priority areas pursued through extra-budgetary sources
- Participation projects
- Participation in regional activities organized by other organizations

Regular programme activities

Activities in this category are divided into two types, namely; theme(s) for high concentration of ROSTAS efforts and routine regular activities. The themes currently selected for high concentration include "Groundwater Protection" and "Rainfall Water Management", while the regular activities include support to regional training courses, strengthening national IHP committees, regional meetings of IHP committees, regional and international conferences, ...etc. Few active working groups have been established in the concentration areas where state-of-the-art reports have been published together with a package of identified priority topics that have been consolidated into project documents prepared for extra-budgetary funding sources.

ROSTAS's involvement in IHP-V will cover almost seven of the eight themes (except for humid tropics) but due to budgetary limitation it may concentrate into three to four themes through its regular budget. Hopefully the other areas, which are very important to the Arab Region, can be tackled through other forms of funding.

Priority areas pursued through extra-budgetary sources

ROSTAS identified many priority themes of regional nature that cannot be financed from ROSTAS modest regular budget. It has prepared outlines, preliminary concept papers or project documents for some of these themes and is actively seeking financial support, from funding agencies, for their execution. Its current individual and joint efforts, in this direction include, among others:

- A water resources assessment project including the updating and restructuring of the document "Water Resources Assessment in the Arab Region"; jointly with ACSAD.

- A comprehensive project on "Groundwater Protection".
- A comprehensive project on "Rainfall Water Management".
- Development of hydrological softwares using multimedia techniques (including CD-ROMS).
- Training and capacity building activity in the water sector, especially in Palestinian Territories.

UNESCO/ROSTAS welcomes cooperation with any regional or international organization in any or all of these activities.

Participation projects

These are projects, outside the regular work plan, financed by UNESCO as a result of direct requests from the countries or associate IGOs of the Arab region. It is unfortunate that, up to now, very few countries of the region have made significant use of this facility in the areas of water resources. Special effort is being made to establish active national IHP Committees to make a better use of this fund, perhaps through a co-ordinated regional project.

Cooperation with other organizations

ROSTAS is responding, whenever possible, positively to requests for cooperation and participation in regional activities organized by other regional and international water agencies. With the shrinking resources globally, it believes that there is a need for closer interagency cooperation in planning and implementing joint priority programmes perhaps through a joint regional project.

CONCLUDING REMARKS

- The per capita annual renewable water resources in the Arab region is by far much lower than the global average.

- This inherited scarcity can be managed through well defined options; important of which are scientific knowledge and cooperation.

- The most outstanding knowledge deficiencies, in the region, have been identified in the paper. Most of these deficiencies are well taken by UNESCO's International Hydrological Programmes (IHP), especially the current IHP-V cycle (1996 - 2001).

- Important features of IHP, IHP-V and ROSTAS activities have been summarized in the paper and recommended as a framework for a regional initiative to alleviate the outlined knowledge deficiencies towards sustainable water resources management.

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Annex 1

LIST OF IHP-V PROJECTS

THEME 1: Global hydrological and geochemical processes

Project 1.1: Application of methods of hydrological analysis using regional data sets (Flow Regimes from International Experimental and Network Data Sets/FRIENDS)

Project 1.2: Development and calibration of coupled hydroecological/atmospheric models

Project 1.3: Hydrological interpretation of global change predictions.

Project 1.4: Strategies for water resource assessment and management under conditions of anthropogenic global climate change.

THEME 2: Ecohydrological processes in the surficial environment

Project 2.1: Vegetation, land use and erosion processes

Project 2.2: Sedimentation processes in reservoirs and deltas

Project 2.3: Interactions between river systems, flood plains and wetlands

Project 2.4: Comprehensive assessment of the surficial eco-hydrological processes

THEME 3: Groundwater Resources at Risk

Project 3.1: Groundwater contamination inventory

Project 3.2: Monitoring strategies for detecting groundwater quality problems

Project 3.3: Role of unsaturated zone processes in groundwater supply quality

Project 3.4: Groundwater contamination due to urban development

Project 3.5: Agricultural threats to groundwater resources

THEME 4:	**Strategies for water resources management in emergency and conflicting situations**
Project 4.1:	International water systems - (a) Conflict analysis and resolution; (b) Development of integrated hydrological information and decision systems for international river basins; (c) Large-scale diversions; systems control, emergency procedures and extreme hydrological conditions.
Project 4.2:	Comprehensive environmental risk and impact assessment
Project 4.3:	Non-structural measures for water management problems
THEME 5:	**Integrated water resources management in arid and semi-arid zones**
Project 5.1:	Hydrological processes in arid and semi-arid zones
Project 5.2:	Water resources assessment in arid and semi-arid zones
Project 5.3:	Water resources management for sustainable development in arid and semi-arid zones
Project 5.4:	Coping with water scarcity
THEME 6:	**Humid tropics hydrology and water management**
Project 6.1:	Hydrological processes in the humid tropics environment and other warm humid regions
Project 6.2:	Land use deforestation, erosion and sedimentation in the humid tropics
Project 6.3:	Integrated water management for sustainable development in the humid tropics
Project 6.4:	Information exchange on regional hydrological processes research and experiences in water resources management

THEME 7: Integrated urban water management

Project 7.1: Non-structural flood control measures to balance risk-cost-benefit in flood control management in urban areas

Project 7.2: Surface and groundwater management in urban environment

Project 7.3: Integrated urban drainage modeling in different climates: tropical, arid and semi-arid, and cold

THEME 8: Transfer of Knowledge, Information and Technology (KIT)

Project 8.1: Formal education at all levels

Project 8.2: Continuing education and professional training at all levels

Project 8.3: Transfer information and technology

Project 8.4: Public awareness issues related to hydrology

Evaluation of Groundwater Resources of United Arab Emirates

Zeinelabidin S. Rizk, Abdulrahman S. AlSharhan and Shizuo Shindo

EVALUATION OF GROUNDWATER RESOURCES OF UNITED ARAB EMIRATES

Zeinelabidin S. Rizk[(1)], Abdulrahman S. Alsharhan[(1)], and Shizuo Shindo[(2)]

(1) Faculty of Science, U.A.E. University
B.O. Box 17551 - Al Ain, United Arab Emirates

(2) Center for Environmental Remote Sensing
Chiba University, Japan

ABSTRACT

During early 1996, over 200 groundwater samples were collected from private wells tapping different aquifers in the U.A.E. Field measurement of groundwater levels and ground-truth information were gathered for remote-sensing studies. The water samples were analyzed for major, minor and trace dissolved constituents, in addition to stable and radioisotopes.

Preliminary results indicate the presence of local, intermediate and regional groundwater flow systems, which affect salinity, quality and type of groundwater. Excessive groundwater pumping has created cones-of-depression ranging from 50 to 100 km in diameter at Al Dhaid, Hatta, Al Ain and Liwa areas. These cones have caused decline of groundwater levels, dryness of several shallow wells and salt-water intrusion problems. Measured depths to groundwater are < 5 m in the Liwa, Diba, Khor Fakkan, Kalba, Shaam and Khatt areas; 10-25 m in Al Shuayb, Madinat Zayed and Al Madam areas; 25-50 m in Al Wagan, Al Hayer, Jabal Hafit, Al Faiyah, Al Jaww plain, Hatta and Masafi areas; 50-100 m in Wadi Al Bih and Al Ain areas; and >100 m in Al Dhaid area.

Low groundwater salinity, 230-1000 milligrams per liter (mg/l), is present in Al Jaww plain, Masafi and Al Shuayb areas. Groundwater salinities of 1000-3500 mg/l are measured in Al Ain, Diba, .Hatta, Khatt and Al Fujairah areas, whereas salinities of 3500-6500 mg/l are recorded in Ras Al Khaimah, Madinat Zayed, Liwa and Dubai areas. Groundwater with >10,000 mg/l of dissolved salts are observed in Al Dhaid, west and south of Al Ain and Kalba areas.

High-temperature groundwater (40-50°C) occurs in all U.A.E. permanent springs and the Jabal Hafit new wells, indicating the deep circulation of such water or the possibility of the presence of radioactive sources. Centers of high-temperature groundwater lie along NNE-SSW striking thrust faults which represent the

western boundary of the Oman Mountains.

The cation dominance in groundwater of U.A.E. has the order: Mg^{2+}> Ca^{2+}> Na^{+}> K^{+} in the eastern part, Ca^{2+}> Mg^{2+} > Na^{+}> K^{+} in the central part and Na^{+}> Ca^{2+}> Mg^{2-}> K^{+} in the western part. The anion dominance has the order: HCO_3^- > Cl^-> SO_4^{2-}>CO_3^{2-} in the eastern part, SO_4^{2-}> Cl^-> HCO_3^-> CO_3^{2-} in the central part and Cl^-> SO_4^{2+} > HCO_3^-> CO_3^{2-} in the western part. The groundwater-dissolved salts are $Ca(HCO_3)_2$ and Mg $(HCO_3)_2$ in the northern and eastern parts, $Na_2(SO_4)$, $CaSO_4$ and $MgSO_4$ in the central part and $MgCl_2$ and NaCl in the western and southwestern parts. The dominant groundwater types are bicarbonates (HCO_3^-) in the northern and eastern parts, sulphates (SO_4^{2-}) in the central part and chlorides (Cl^-) in the western and southwestern parts. The Cl/ (CO_3+HCO_3) and Na/Cl ratios indicate the presence of salt-water intrusions problems in Ras Al Khaimah, Al Dhaid, Diba, Kalba, Dubai-Jabal Al Dhanah, Madinat Zayed, Liwa and Al Ain.

Groundwater in the eastern mountains and the flanking gravels is mainly fresh (<1500 mg/l total dissolved solids) and can be used for all purposes. Groundwater is hard to very hard in the northeastern part, Al Dhaid, Kalba, Al Khaznah and along the western coast. The calculated Sodium Adsorption Ratios (S. A. R.) show that the groundwater in the northern and eastern parts has little harmful effect on plants and soils (S. A. R. <10), whereas the groundwater along the western coast, west of Al Ain and east of Liwa has high S. A. R. values and can be very harmful to plants and soils when used for irrigation (S. A. R. >26).

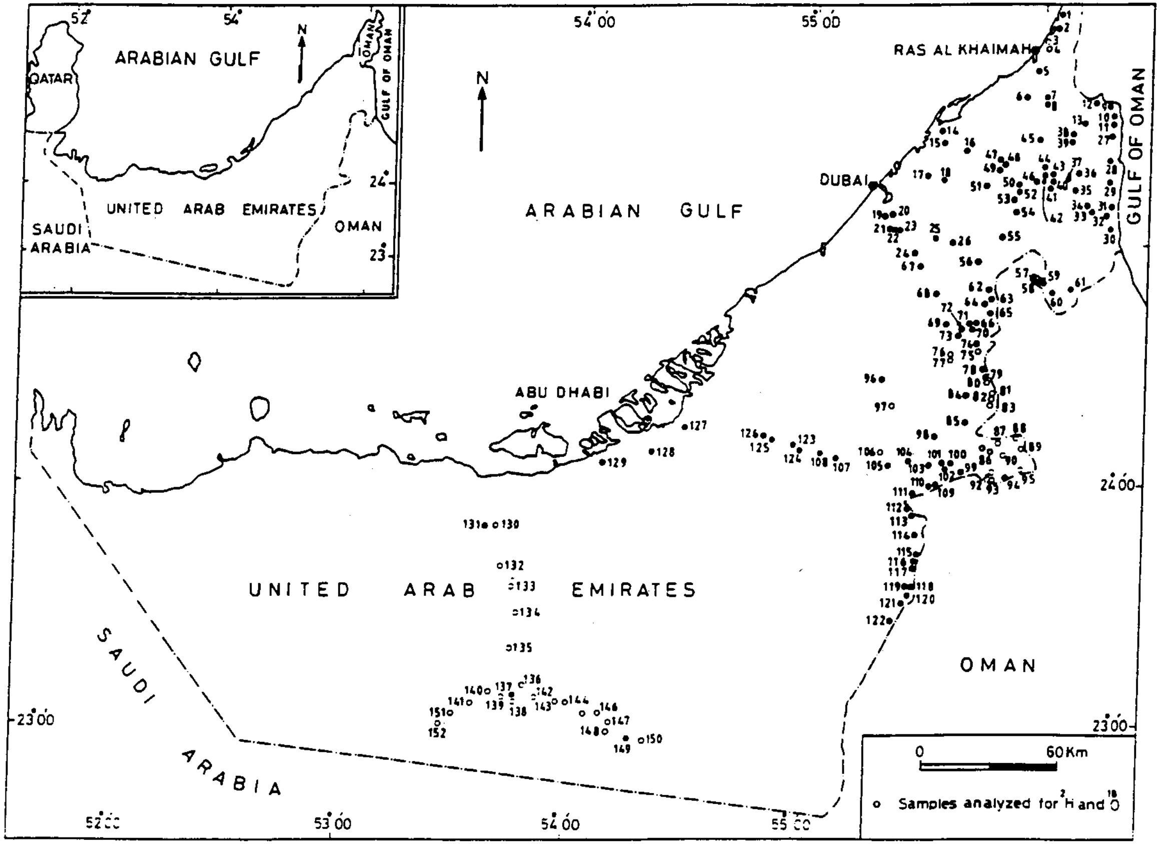

Figure 1. Location map of U. A. E. and the water wells sampled for chemical and isotope analyses.

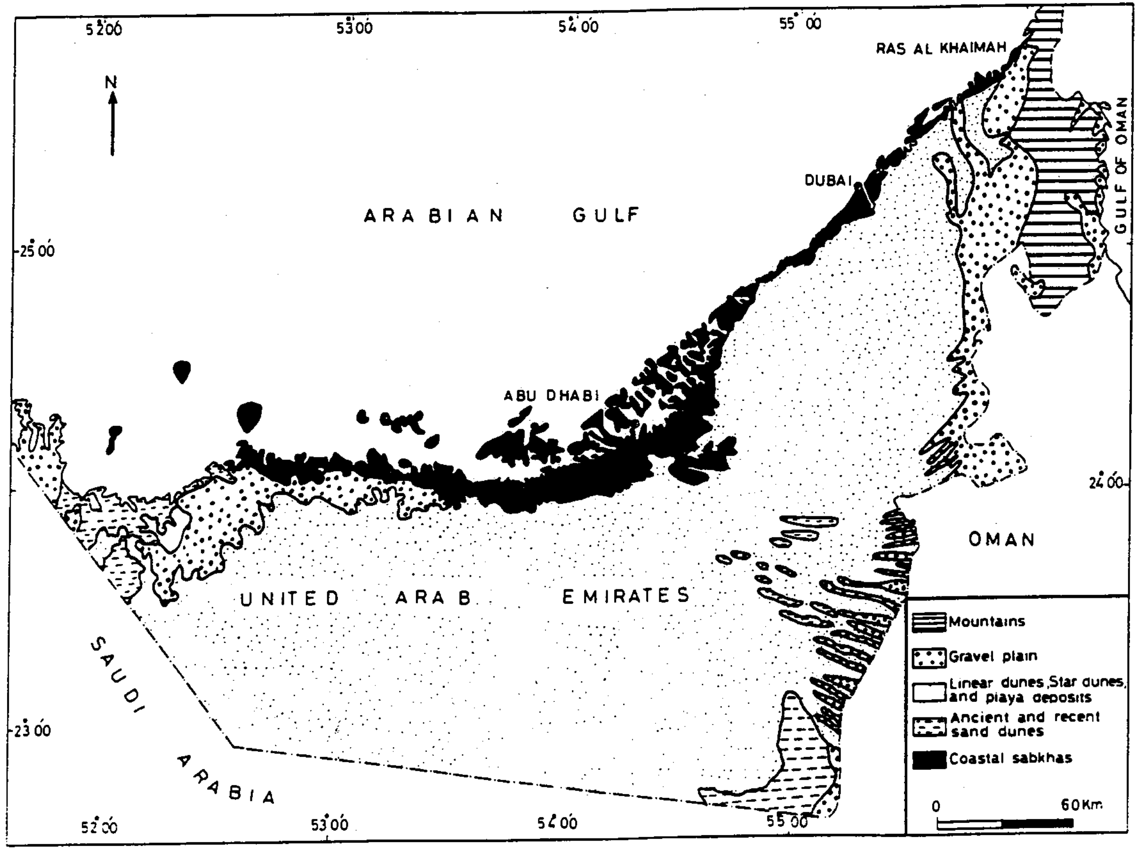

Figure 2. Geomorphological map of U. A. E., simplified from the United Arab Emirates National Atlas (1993).

INTRODUCTION

In cooperation with the Center for Environmental Remote Sensing (CEReS), Chiba University, Japan, the Faculty of Science, U.A.E. University, initiatedan extensive groundwater evaluation study in February 1996. The field survey covered the whole U.A.E.; including the limestone aquifer in the north, fractured ophiolite rocks in the east, eastern and western coastal strips, gravel aquifers flanking the eastern mountain ranges and the sand dune aquifers in the west, south and southwest.

Objectives of this study are to investigate different aquifers in U.A.E. in terms of their hydrogeological conditions, hydrogeochemical characteristics, recharge mechanisms and suitability of their water for different uses.

During late February-early March, 1996, a field survey was conducted to achieve these objectives. Over 200 groundwater samples were collected from private wells and analyzed for major ions in the Chiba University, Japan. In August, 1996, 42 of collected water samples were analyzed for ^{18}O,^{2}H and ^{3}H in the Isotope Hydrology Laboratory of the International Atomic Energy Agency (IAEA), Austria (Fig. 1).

GEOMORPHOLOGY AND GEOLOGY

Study of topographic maps and satellite images enabled recognition of the following geomorphic features in U.A.E.: mountains, gravel plains, sand dunes, coastal zones and drainage basins (Fig. 2).

Mountains

The eastern mountains of U.A.E. extend for 155 km between Shaam in the north and Al Ain in the south, with an average width of 10 km in the north, 38 km in the middle and 27 km in the south. The elevations of the mountain peaks vary between 500 and 900 m above sea level. Some salient peaks, however, may reach an elevation of 2,000 m. Within U.A.E., these mountains are dissected by the drainage nets of 58 basins, which vary in area between 5 km^2 (Wadi Dadnah, Al Fujairah) and 5,000 km^2 (Wadi Al Bih, Ras Al Khaimah).

The U.A.E. eastern mountains can be divided into three major parts: Rus Al Jibal massif in the north, Diba zone in the middle and northern Oman mountains in the south (Finzi, 1973). The Rus Al Jibal massif consists predominantly of a carbonate sedimentary sequence that ranges in age from Triassic to Lower Cretaceous. In general, the area is characterized by broad folding, block faulting and complex local thrusting. The Diba zone is an elongated NE-SW trending topographic depression, separating the Rus Al Jibal Musandum shelf in the northwest from the Semail ophiolite sequence in the southeast. The northern part of the Semail ophiolite nappe of the Oman mountains is composed of a repeated sequence caused by internal low-angle thrust faults. The ophiolite complex is divided frombaseto top into: anultramafic mantle sequence, layered peridotite, coarse-grained gabbros, fine-grainedgabbros, sheeted dyke complex and extrusive lava. Jabal Hafit is an anticlinal Tertiary structure plunging south in Oman and north in U.A.E. (Whittle and Alsharhan, 1994). It extends 29 km, 15 km of which are within the U.A.E. and the rest are in Oman. It has an average width of 5 km and a maximum elevation of 1,160 m (east of Al Ain Al Faydah). Jabal Hafit is an asymmetrical doubly-plunging anticline that has a whaleback form with beds dipping to the east and west off its north-south trending axis. Dip angles vary between 60° and 80° on the eastern limb and between 22° and 26° on the western limb (Hunting, 1979).

Gravel Plains

Gravel plains bound the northern Oman mountains from the east and west. The eastern gravel plain is a narrow strip, 4 km (Al Fujairah) to 10 km (Kalba) wide and 70 km long. It extends between Diba in the north and Khatm Al Mallaha in the south, and is bounded by the Gulf of Oman on the east and the northern Oman mountains on the west.

The western gravel plains extend for some 160 km as a long, narrow strip from Ras Al Khaimah in the north to the Al Jaww plain, east of Al Ain city, in the south. The plains exist at the outlets of main wadis, which controls their shape and width. They occupy the area between the northern Oman mountains on the east and the sand dune fields on the west. The western gravel plains have a gentle slope from east to west with an average gradient of 0.001 (Ghoneim, 1991).

The gravel plains are composed of alluvial sands and gravels, which gradually decrease in size from east to west. The continuity of the western gravel plain is locally interrupted by sand dunes and Al Fayah mountain range.

Sand Dunes

Sand dunes cover 74% of the total area of the U.A.E. and occupy a substantial part of the desert plains. The dunes occupy a rather triangular area; its apex lies in the north at Ras Al Khaimah, its base draws the U.A.E. - Saudi Arabia border in the south, its eastern side runs parallel to the pediment plains and its western side runs parallel to the western coast.

The aeolian dune system in U.A.E. is a part of the well known sand sea of Al Rub Al Khali which extends beyond the borders of U.A.E. into Saudi Arabia and Oman. Landsat satellite images show that most of the U.A.E. area is occupied by different types of sand dunes. Embabi (1991) used satellite images to study the dune types, patterns, generations and the factors affecting them. He observed that the dunes rise from several meters in the north along the coast to 200 m above sea level in the Liwa area.

The dunes of U.A.E. include linear, barchan, barchanoid, transverse and star types. The dunes include both simple and compound patterns, which are mainly controlled by sand supply, meteorology, topography, lithology and geological structures.

Coastal Zones

The western coast of U.A.E. is an area of tidal flats and sabkhas which border the Arabian Gulf. These flats comprise sandy silt-sized carbonate sediments with anhydrite and halite (United Nations, 1982).

The eastern coast is composed of a series flats filling the embayments between promentories into the Gulf of Oman. South Khor Fakkan, the flats and wadi fans coalesce to form an almost continuous littoral strip between the mountains and the sea. The sand and gravel flats contain fresh water which drain the main wadis toward the sea. Several wadis such as Wadi Ham drains eastwards to the Gulf of Oman can witness flash floods which do not last longer than few hours.

Drainage Basins

In spite of the absence of permanent streams in U.A.E., there are numerous dry drainage basins that can carry water during occasional heavy rain storms. Streams discharging these basins start at the eastern mountainous region and drain either eastward in the Gulf of Oman or westward in the direction of the Arabian Gulf in the north and the sand dune fields in the southwest.

The drainage basins can carry large amounts of water over a very short period of time, forming flash floods that can cause groundwater recharge under favorable lithological and confinement conditions.

The eastern mountains are dissected by 70 drainage basins,58 of which lie within U.A.E. The area of these basins vary from 5 km^2 (Wadi Dhanna) and 5000 km^2 (Wadi Al Bih). Among these basins, 54 have areas more than 10 km^2, indicating their capability of carrying large amounts of flood water, especially the basins of the southern region which drain low permeability igneous and metamorphic rocks.

The drainage basins in the eastern mountains need detailed studies for estimation of their water budgets and calculation of their run off capacities during heavy rain storms.

STRATIGRAPHY

The water-bearing units in U.A.E. include a rock sequence ranging in age from the Permian to Quaternary periods (Figures 3 and 4). The rock types, geological structures and climatic conditions are the main controls on the quantity and quality of groundwater in U.A.E.

GEOLOGIC STRUCTURES

The U.A.E. can be differentiated into the following five structural provinces from north to south: Rus Al Gibal, Diba province, ophiolite sequence, wadi Hatta province, and the western area (Fig. 5). The following is a brief discussion on each of these areas (Fig. 5):

Rus Al Jibal

Rus Al Gibal area is characterized by thrust faults that are inclined in the east and south directions. Sometimes the thrust plain slopes towards east to the zone of overturned and recumbent folds.

Diba Zone

The Diba zone represents the most important geologic structure in the northern Oman mountains. This province is topographically low and extends for 30 km from northeast to southwest, with an average width of 20 km. The Diba zone is considered a tectonic window that separates between Musandum calcareous sequence in the north and the ophiolite sequence in the south. The Diba zone is occupied by stratified rocks of tectonic boundaries.

Ophiolite Sequence

The northern part of this sequence is dissected by the Wadi Ham fault (northwest-southeast) and wadi Thawban fault (east-west). A 10 km lateral displacement along the contact between gabbroic rock units on both sides of wadi Ham can be noticed. There is also a clear change in rock type on both sides of the valley.

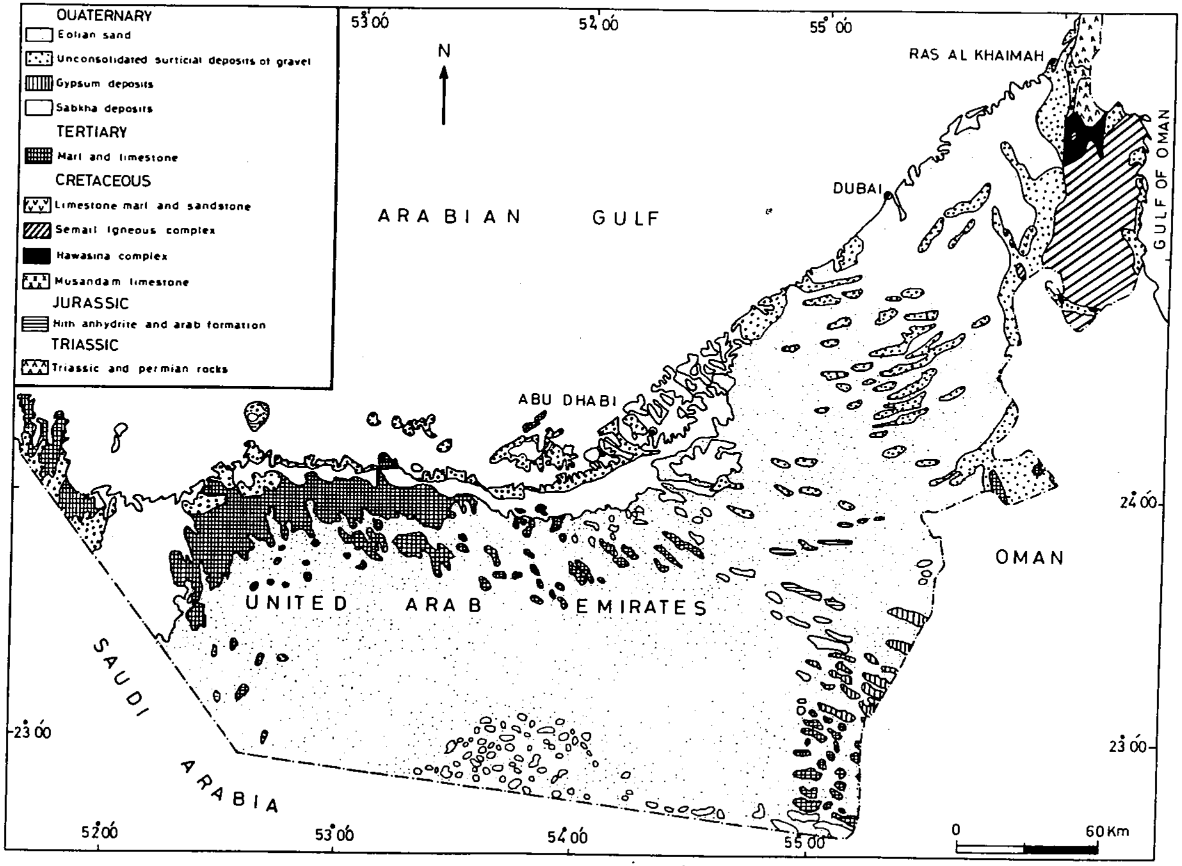

Figure 3. Geologic map of U. A. E., simplified from the geologic map of U. A. E. by Kansas Geological Survery (1990).

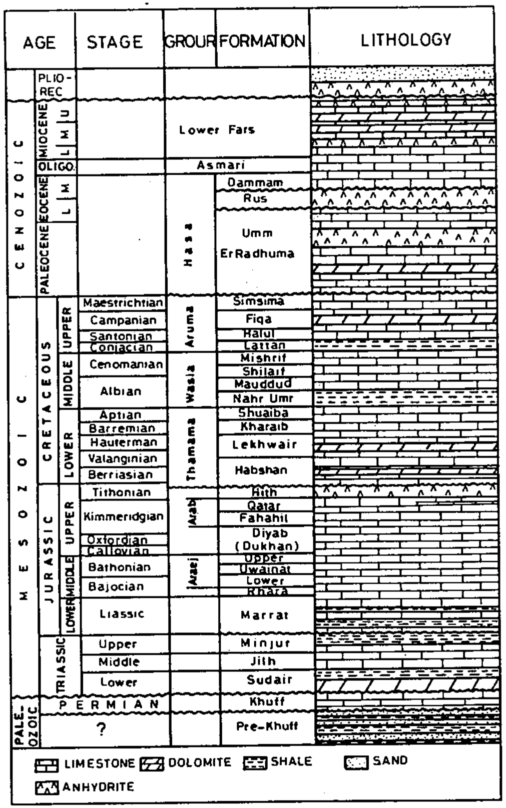

Figure 4. Generalized stratigraphic column for Abu Dhabi area, compiled from Schlumberger (1981) and Alsharhan (1989).

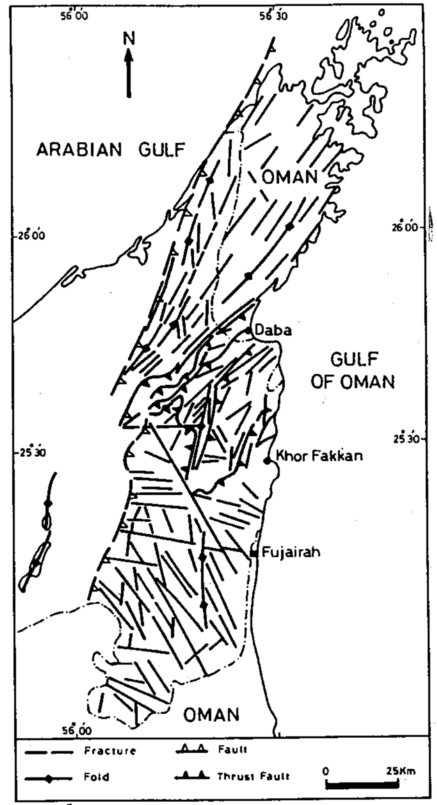

Figure 5. Faults and fractures on the eastern mountain range in the United Arab Emirates (El-Etr at al., 1994).

Hatta Zone

Hatta zone represents a tectonic window which is similar to a great extent to Diba zone. The folding and rock stratification in this zone are parallel to the longitudinal direction of the tectonic opening in the west-northwest direction.

Western Region

The post Late Maestrichtian calcareous deposits and associatedrocks were subjected to folding along the western slopes along the northern Oman mountains. The Upper Cretaceous - Lower Tertiary boulder beds and calcareous rocks represent the boundary between the north Oman mountains in the south and Schisa sands in the north.

HYDROGEOLOGY

The rainfall over the U.A.E. shows a pronounced variation in space and time, depending on climatic conditions, geographic location, local topography and rainfall deriving mechanism. Most of the rain falls in the winter months of December, January, February and March, among which March has the highest records. This rain is light to moderate, widespread and generally related to the frontal mechanism. Isolated rain events are also observed in summer as a result of the convection mechanism associated with the monsoon currents. These storms are generally heavy, isolated and confined to the eastern mountains and their footslopes. Despite its limited area (5% of the total area of the U.A.E.), the eastern mountain range receives about 30% of the total annual rainfall. Also, about 90% of the total annual rainfall in U.A.E. occurs during February and March.

During the 1934-1996 period, the mean annual rainfall in U.A.E. fluctuated between 10 mm in 1946 and 340 mm in 1957. Isohyetal map of U.A.E. for the 1976-1996 period shows that the mean annual rainfall reaches its maximum (170mm in Masafi) in the northeast and its minimum (16 mm in Bu Hasa) in the southwest (Fig. 6). This figure shows that the rainfall in U.A.E. increases in the north and east and decreases in the south and west.

A plot of the mean annual rainfall for the 1934-1996 period shows the presence of cycles of about 10 years during which above average rainfall occurs (Fig. 7). Similar cycles were observed by Rizk et al. (1996) on their study of the Al Ain area. The importance of these cycles is that it produces enough rain which can contribute to groundwater recharge.

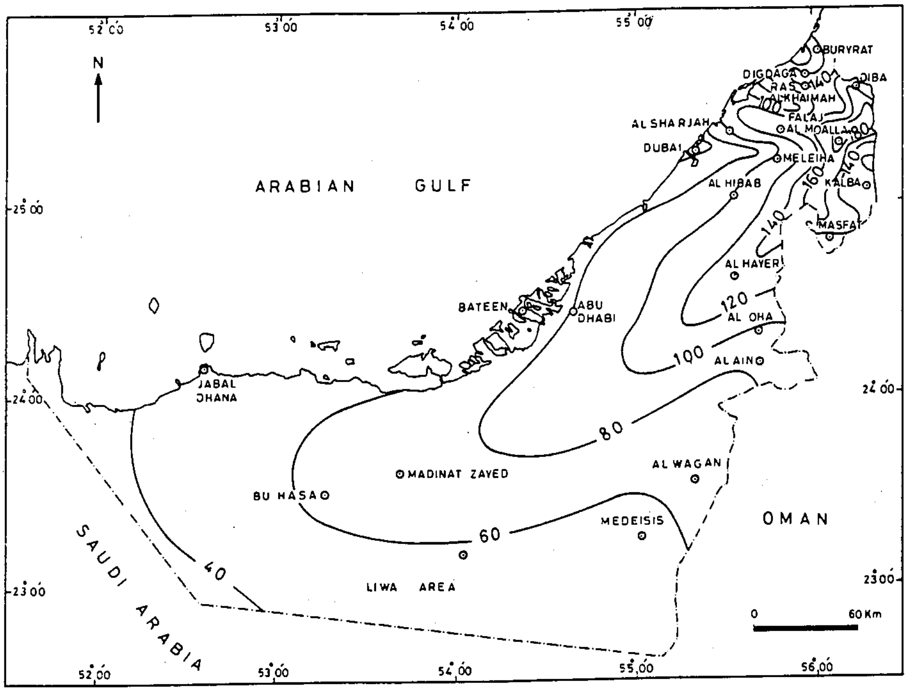

Figure 6. Iso-hyetal map (mm/yr) of U. A. E. for the period 1976-1996, based on data from the Ministry of Agriculture and Fisheries. Contour interval = 10 mm.

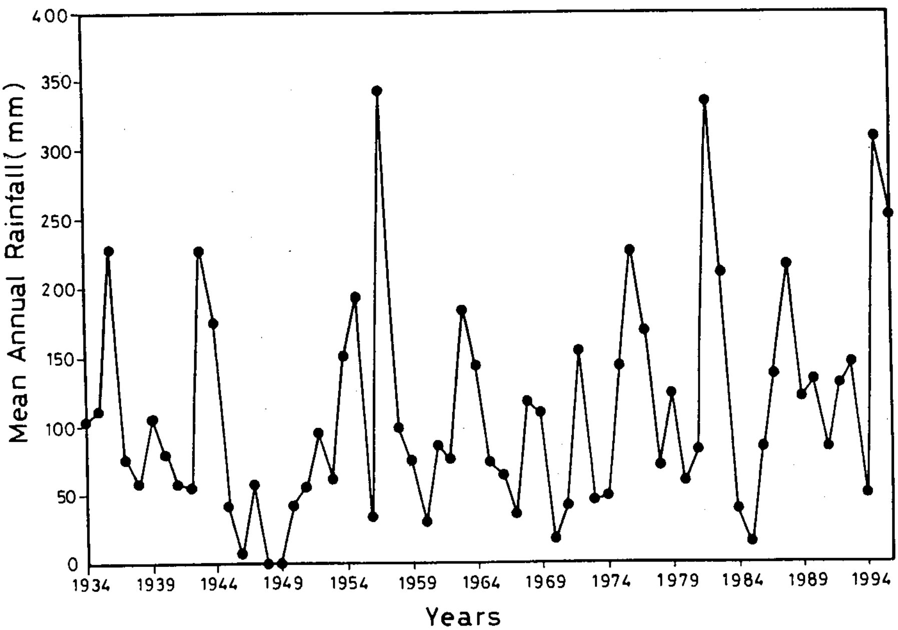

Figure 7. A plot of the mean annual rainfall (mm) in U. A. E. for the period 1934-1996.

Hydraulic Heads

Field measurements show that the depths to groundwater are < 5 m in the Liwa, Diba, Khor Fakkan, Kalba, Sbaam and Khatt areas, 10-25 m in the Al Shuayb, Madinat Zayed and Al Madam areas, 25-50 m in Al Wagan, Al Hayer, Jabal Hafit, Al Faiyah, Al Jaww plain, Hatta and Masafi areas, 50-100m in Wadi Al Bihand Al Ain areas, and >100 m in Al Dhaid area. These measurements revealed the presence of four major cones of depressions centered at Al Dhaid, Hatta, Al Ain and north of Liwa. Water depths in the first three cones is greater than 100 m, and water depth in the center of the fourth cone is about 50 m (Fig. 8).

The presence of cones-of-depression is related to excessive groundwater pumping and limited annual replenishment of exploited aquifers. These cones cause decline of groundwater levels and dryness of several shallow wells (Al Dhaid area), increase of groundwater salinity and induction of salt-water intrusion. Two west-east progressing salt water tongues south of Dubai and north of Al Ain are observed in the sand and gravel aquifers of western U.A.E. (Fig. 8). Salt-water intrusion is also observed west of Kalba and north of Khor Fakkan along the eastern coast, and at Wadi Al Bih on the northwestern coast. Salt-water intrusion is not only limited to coastal areas because salt water can move upward 'upconing' from deep horizons of the aquifers (Al Dhaid and Al Ain areas). Saline groundwater under sabkha areas (such as Sabkhat Al Thuwaymah, west of Al Ain city) can move laterally under the effect of heavy pumping to intrude into fresh groundwater (Al Ain area).

Field measurement of depth to water and ground elevations from topographic map were used to construct a rough hydraulic head map (Fig. 9), mainly for the sand and gravel aquifers. This map shows that the eastern mountains are the main recharge area for groundwater in U.A.E., whereas the Arabian Gulf and the Gulf of Oman are the main discharge areas. Local discharge areas are encountered west of Al Ain, Liwa and the western coastal sabkhas.

The groundwater flow in the northern limestone aquifer is mainly controlled by fractures, with a net flow towards the Arabian Gulf. Khatt springs (Ras Al Khaimah) originate where a fault structure interrupts the continuity of these fractures. The only flowing artesian well in U.A.E. was observed in farm located southwest of the Khatt springs. Groundwater flow in the ophiolite sequence is also controlled by fractures. Maddab spring (Al Fujairah) originates along an east-west fault dissecting these rocks. The groundwater flow in the sand and gravel aquifers on the western side of the mountains is generally from east to west and northwest between Latitudes 24° 00° and 26° 00° N and from southeast to northwest between Latitudes 22° 00° and 24° 00° N. Toth (1963) suggested that most flow nets can be distinguished into local, intermediate and regional

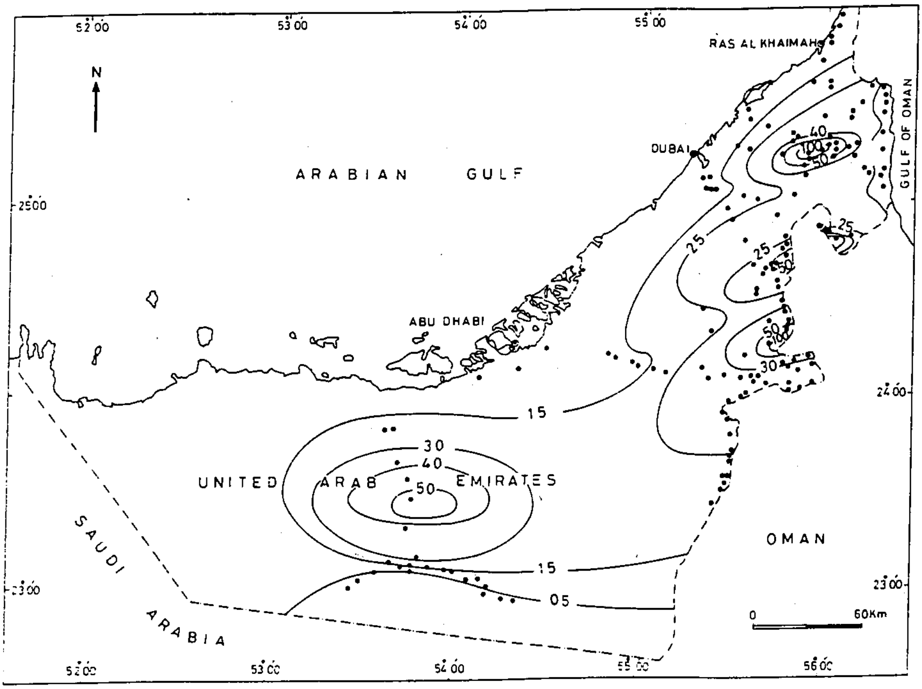

Figure 8. Depth to groundwater (m) in shallow wells tapping different aquifers in U. A. E., measured in March 1996. Black circles represent data points. Contour interval = 10 m.

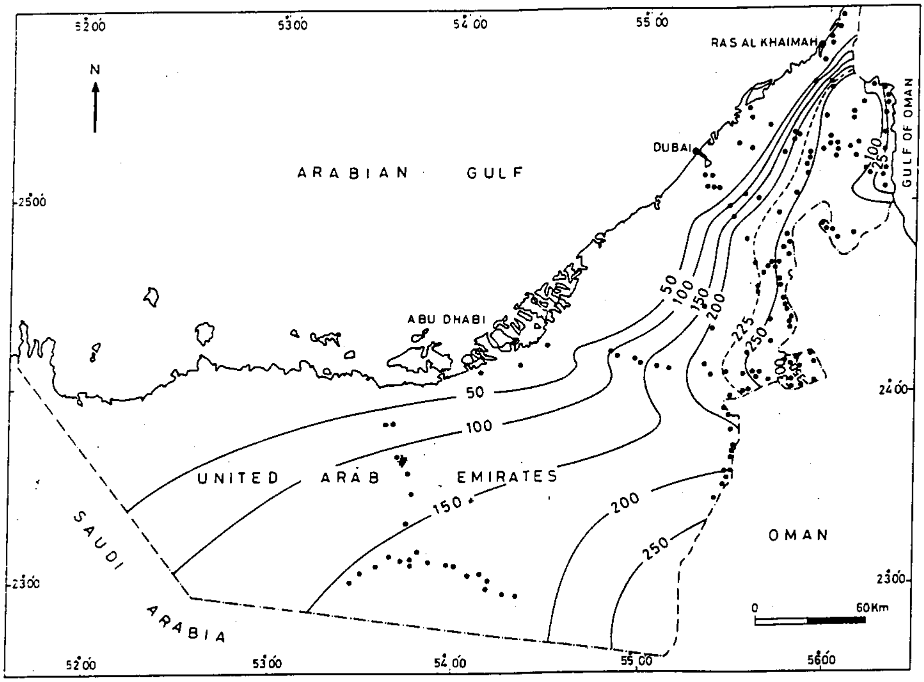

Figure 9. Hydraulic head (in meters above mean sea level) of the sand and gravel aquifers in U. A. E., measured in March 1996. Black circles represent data points. Contour interval = 50 m.

systems of groundwater flow. However, the flow systems that are actually present in an area depend on local topography and basin-shape geometry. Detailed study of groundwater flow in U.A.E. points out to the presence of local, intermediate and regional groundwater flow systems (Fig. 10).

Local Groundwater Flow Systems

These systems are limited to the eastern mountains where the hydrologic cycle is relatively fast and groundwater has a short residence time. Water of these systems has a low salinity (500-1500 mg/l) and belongs to the HCO_3^- water type. Magnesium ion (Mg^{2+}) is the dominant cation. Groundwater of local flow systems has a good quality, such as those of the Masafi and Al Jaww plain areas. It seems that Khatt (Ras Al Khaimah) and Maddab (Al Fujariah) springs discharge a local groundwater flow systems.

Intermediate Groundwater Flow System

Inland sabkhas represent the main discharge areas for ground water of this system. Its groundwater is mainly brackish (1500-10000 mg/l), has a moderate residence time and belong to the SO_4^{2-} water type. Calcium ion (Ca^{2+}) is the dominant cation. Because its relatively high salinity, groundwater of this system has limited uses. Al Ain Al Faydah (Al Ain) seems to discharge this system.

Regional Groundwater Flow System

Coastal sabkhas represent the main discharge areas for groundwater of this system. Its groundwater is mainly saline (>10000 mg/l), has a long residence time and belong to the Cl^- water type. Sodium ion (Na^+) is the dominant cation.

AQUIFERS

Based on hydrogeological conditions and hydrochemical characters, the aquifers of U.A.E. are: the limestone aquifers in the north and east, ophiolite aquifer in the east, gravel aquifers flanking the eastern mountain ranges and the sand dune aquifer in the west and southwest (Fig. 11).

The Limestone Aquifers

This aquifer occurs in the northern part of U.A.E. and is predominantly composed of limestones and dolomites. In Wadi Al Bih, these rocks are well stratified, hard, dens and non-porous at the surface, indicating extensive internal karstification. The carbonate sequence reaches several thousands of meters, forming the Hajar Group which spans the stratigraphic period of Permian to Mid-Cretaceous.

The tectonic structure in the limestone can be described as antiforms of regional dimensions. The trend of the anticlinal axes is north-south, with a predominant plunging towards south in the Wadi Al Bih area. A major fault directed north-south follow the straight stretch of Wadi Al Bih opposite to the mouth of Wadi Qada'ha. This fault practically limits the anticlinal core to the east. There are some transverse tectonic elements along Wadi Al Bih (Electrowatt, 1981).

The Early Eocene carbonates of the Rus Formation constitute an aquifer in the Jabal Hafit area south of Al Ain city. These carbonates are characterized by extensive dolomitization. Porosity is vertually nill in these rocks except for infrequent unfilled fractures, vugs and oomolds, due to cementation and chertification (Whittle and Alsharhan, 1994).

Ophiolite Aquifer

The ophiolite sequence is jointed and fractured and has been subjected to faulting. The main fault system runs in a northwest-southeast direction. Electrowatt (1981) described the ophiolite Formation of the Samail Suite as being typically medium-grained gabbro and fine to medium-grained diorites.The jointing, faulting and weathering of the Samail-Hawasina beds of the northern Oman mountains give rise to good aquifers. Groundwater in this area occur only in joints and fractures (Eutec, 1995).

Gravel Aquifers

The largest reserve of fresh groundwater in U.A.E. occurs in the alluvial deposits of the piedmont plains bounding the eastern mountains from the east and west. These aquifers can be distinguished into the eastern gravel aquifer, the northwestern gravel aquifer and the western gravel aquifer.

The eastern gravel aquifer is composed of a series of alluvial flats filling the embayments between promontories of rock spurs into the Gulf of Oman. South of Khor Fakkan, the flats and wadi fans coalesce to form an almost continuous littoral strip between the mountains and the sea. The fans near the mountains comprise rock and coarse gravel which become progressively finer in size as the distance from the mountain increases. The aquifer contains fresh groundwater which drains from the wadi fans towards the sea.

The northwestern gravel aquifer occurs as thin lenses under the sands, and in places, as buried alluvial channels entrenched in the bedrock. The presence of

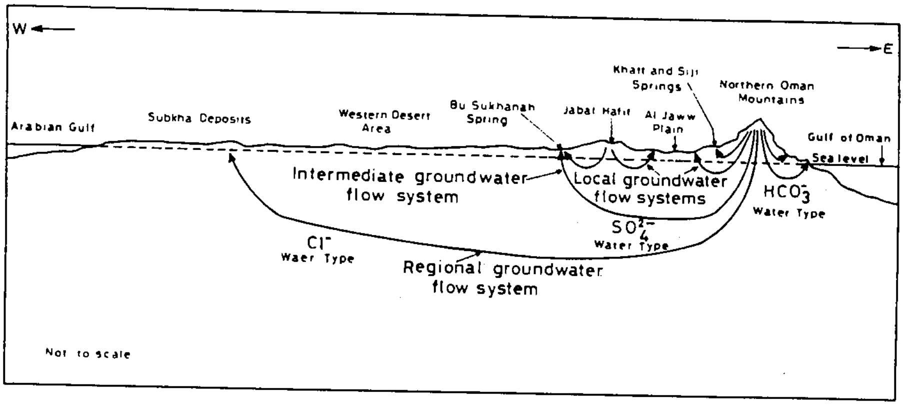

Figure 10. Diagram illustrating different flow systems identified in U. A. E., based on hydrological, hydrochemical and isotopic characteristics of groundwater.

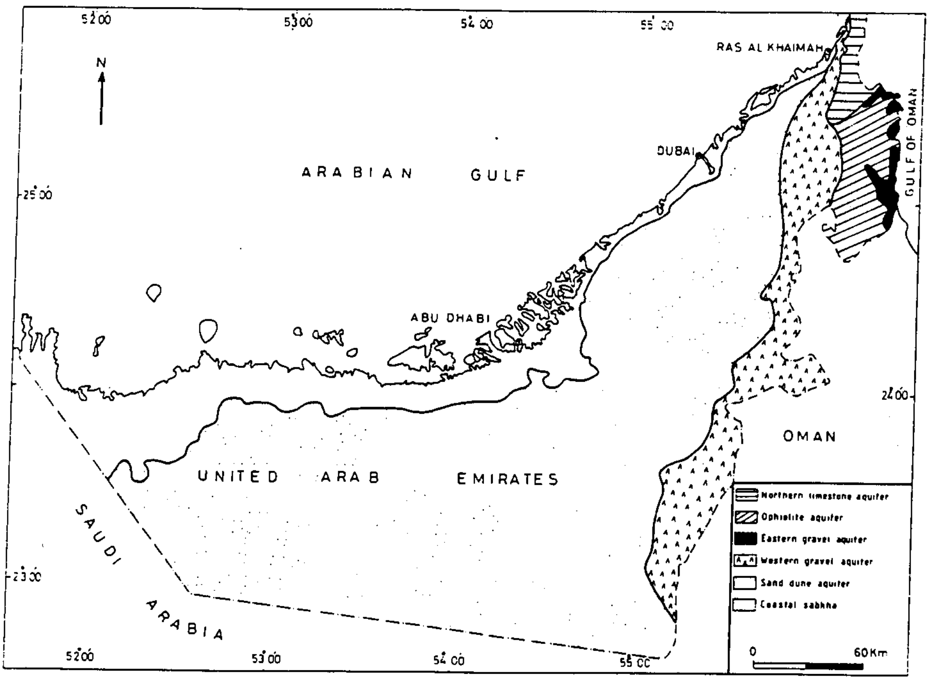

Figure 11. The main water-bearing units (aquifers) identified in U. A. E., based on different hydrological, hydrochemical and isotopic characteristics.

these channels is associated with low-salinity groundwater. An example of these channels was pointed out by Rizk et al. (1995) on their work on Al Ain area. Deposits of gravel have been penetrated within the Quaternary sands in nearly all boreholes drilled in the gravel plain at depths of 60 m below the ground surface and at distances up to 70 km from the eastem mountains (United Nations, 1982).

Quatemary alluvium of the westem gravel aquifer is composed of about 60 m sequence of sand and gravel with thin interbeds of silt and clay. Most of the alluvium was derived from the opiolitic Oman mountains. In the north and west of AlAin, present-day wadis are located between NE-EW trending sand dunes. Recharge of the gravel aquifer in the Al Ain area comes from rain that fall on the westem flank of the Oman and run through wadis where it infiltrates recharging the aquifer. Sir Alexander Gibb and Partners (1970), Hydroconsult (1978), and German Engineering (1982), prepared water-table maps for the gravel aquifer in the Al Ain area. Woodward and Menges (1991) used oil exploration uphole seismic data for constructed water-table map of the gravel aquifer in the Al Ain area. This map suggests that buried paleodrainage network contain saturated alluvial fill and may constitute major fresh water aquifers in the Al Ain area.

Sand Dune Aquifer

Sand dunes cover about 74% of the total area of U.A.E. and gradually increase in elevation from sea level at the westem coast till they reach 250 m above ground level at the Liwa - Al Batin basin in the south central part.

Sand dunes are the least studied aquifer in U.A.E. The Groundwater Research Project of the National Drilling Company (NDC) and the United States Geological Survey (USGS) discovered a fresh water aquifer in the Quatemary sand dunes between Liwa and Madinat Zayed. Based on preliminary hydrogeological investigations, we can claim the presence of a similar fresh water mound in the sand dunes of the Bu Hasa oil field. Exploration of the sand dunes between Al Wagan and Liwa may lead to the discovery of similar fresh water lenses

The Liwa area is covered by undifferentiated eolian sands and sabkha deposits. Eolian deposits consist of medium to very fine-grained sand with silt composed of quartz, carbonates and heavy minerals. The sabkha deposits occur between dunes, mainly south of the Liwa Crescent area, and are composed of thin sand and silt depoists. The thickness of this unit is highly variable, varying between 50 and 150 m.

WATER CHEMISTRY

The study of dissolved chemical constituents in groundwater of U.A.E. reveals the effect of rainfall, geology and hydrogeological conditions on water chemistry quality, and suitability for different uses.

The electrical conductance (E. C.) (μmohs/cm), watertemperature(°C)and hydrogen-ion concentration (pH) were directly measured in the field. The samples were then analyzed for major cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) and anions (CO_3^{2-}, HCO_3^{-}, SO_4^{2-} and Cl^{-}) in the Chiba University, Japan.

Physical Properties

The temperature, E. C. and pH of collected groundwater samples were directly measured in the field. In this respect, high temperature is the most important physical property characterizing U.A.E. groundwater.

Water Temperature

Measured groundwater temperatures varies between 22°C along the eastem coast and 51°C in water wells penetrating the Jabal Hafit Eocene limestone aquifer (Fig. 12).

Centers of high groundwater temperatures are observed in springs and wells of Khatt (Ras Al Khaimah), Al Dhaid (Al Sharijah), Hatta (Dubai) and south Al Wagan (Abu Dhabi) areas. These centers lie along a NNE-SSW striking thrust fault which represents the westem boundary of the northem Oman mountains (Fig. 5). A separate high groundwater temperature center is located between Madinat Zayed and Liwa from which groundwater temperature decreases in all directions. It is believed that high-temperature groundwater is related to the groundwater flow systems or the presence of a radioactive source.

Toth (1963) suggested that most flow nets can be distinguished into local, intermediate, and regional systems of groundwater flow. However, the flow systems that are actually present in an area depend on local topography and basin-shape geometry. Water wells and springs discharging local groundwater flow systems are of low salinity and their temperature are close to the mean annual air temperature. In contrast, water of the springs discharging regional groundwater flow systems is highly mineralized and of an elevated temperature (Fetter, 1988). It is likely that Al Ain Al Faydah spring (Al Ain) obtains most of its water through an intermediate groundwater flow system that starts at the northem Oman mountains in the east. This explains the spring's high-water temperature and TDS contents.

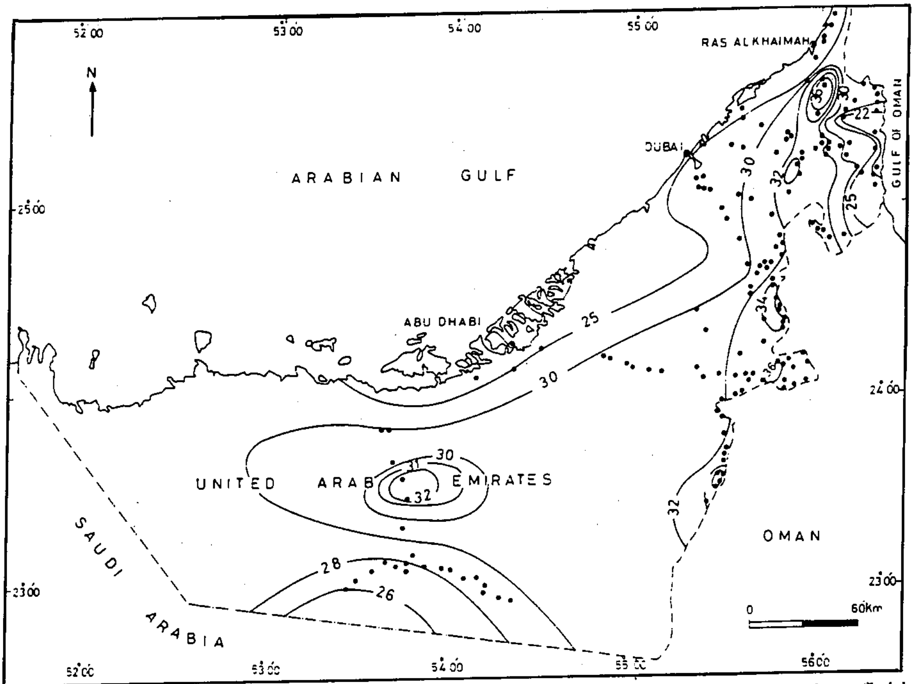

Figure 12. Iso-groundwater temperature (°C) contour map in U. A. E., based on field measurements in March 1996. Black circles represent data points. Contour interval = 2 °C.

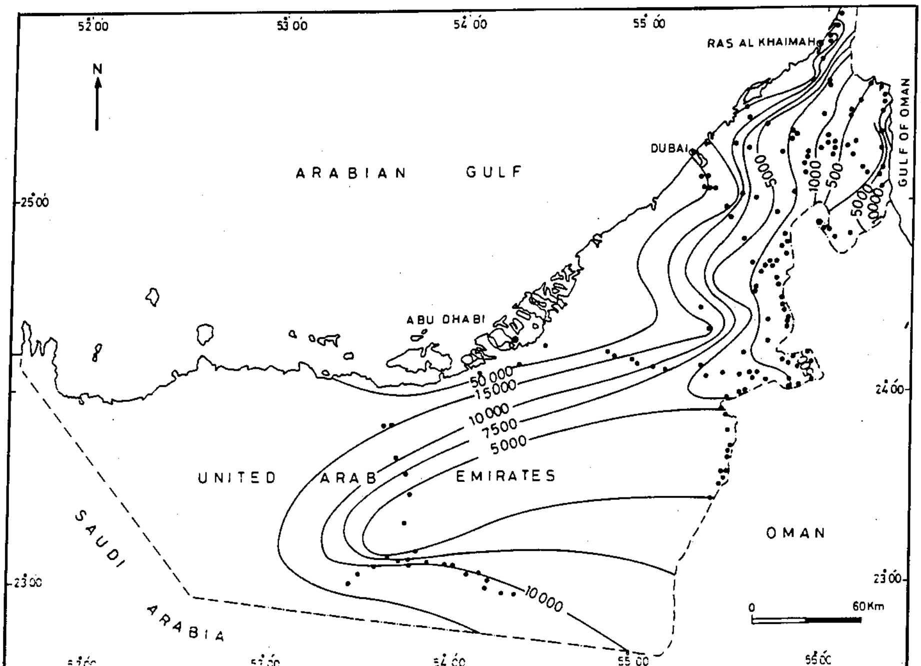

Figure 13. Electrical conductivity (µmohs/cm) of groundwater in U. A. E., measured in March 1996. Black circles represent data points. Contour interval = 5000 µmohs/cm.

El-Shamy (1990) mentioned that Terratest (1975) pointed out that the joints and bedding plains of some calcareous rocks of Jabal Hafit containblack organic deposits that contain 20.7 parts per million (ppm) Uranium. He also attributed the lack of these black deposits in some layers to its leaching by water discharging into Al Ain Al Faydah spring. According to him, the heat associated with radioactive decay of uranium will then rise the water temperature in the spring. Recently, the NDC-USGS measured high radon counts, suggesting a radioactive source.

Electrical Conductivity (E.C.)

The electrical conductance (E.C.) of groundwater samples collected from U.A.E. during early 1996 varies between 252 on the Al Jaww plain, east of the Al Ain city, and 173,000, µmohs/cm in a sabkha area along the Al Ain-Abu Dhabi road(Fig. 13).

Salt-water intrusion as a result of heavy groundwater pumping is noticed south of Dubai, west of Suweyhan and southwest of Al Ain. It is also observed north of Khor Fakkan and west of Kalba along the eastern coast.

The Diba-Hatta line represents a water divide along which the electrical conductivity is low (500 µmohs/cm), increasing in the west and east directions along the groundwater flow paths. A local fresh water lens is observed along the Madinat Zayed-Liwa road centered at Well No. 135 (Fig. 1). Potential for presence of similar fresh water pockets is possible within the triangular area between Al Wagan, Liwa and Um Alzamoul.

The E. C. contour map suggests the presence of hydraulic connection between Al Ain and Liwa areas. However, this assumption needs further investigations.

Hydrogen-Ion Concentration (pH)

The pH of water is related to its quality and affects, to a great extent, its suitability for different uses. The hydrogen-ion concentration of shallow groundwater in U.A.E. varies between 5.37 near the western coast, southwest Abu Dhabi, and 8.18 west of Al Ain city. Generally, the pH of shallow groundwater inU.A.E. increases from the coastal zones towards the eastern mountains. High pH values are encountered in areas dominated by limestone aquifers such as Wadi Al Bih basin (Ras Al Khaimah), and Jabal Hafit (Al Ain).

Major Cations

The sequence of cations dominance in ground water of U.A.E. has the order:

$Mg^{2+} > Ca^{2+} > Na^{+} > K^{+}$ in the eastern part, $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$ in the central part, and $Na^{+} > Ca^{2+} > Mg^{2+} > K^{+}$ in the western part.

Iso-concentration contour maps of Ca^{2+}, Mg^{2+}, Na^{+} andK^{+} ions show the sarne general pattern. Differences in this pattern are related to changes in lithology, hydrogeology of groundwater extraction rates.

The Ca^{2+} concentrations increase towards west and northwest as the percolation of rainwater causes dissolution of limestones dominating these areas and enriching groundwater with this ion. In the central and southern parts, Ca^{2+} content increases along the direction of groundwater flow. In the eastern gravel aquifer, however, the Ca^{2+} amounts are low because of the lack of carbonate rocks, relatively fast groundwater flow and hard dissolution of Ca-rich ophiolitic rocks.

The Mg^{2+} iso-concentration map shows its general increase in the direction of groundwater flow. The main source of Mg^{2+} in gravel aquifers is the dissolution of Mg-rich ophiolitic rocks in northern Oman mountains. High Mg^{2+} contents are also observed in groundwater close to the eastern and western coasts.

With difference in magnitude, Na^{+} and K^{+} contents show a similar pattern. Both ions exhibit low concentrations near the waterdivide, increasing inthe east, northwest, west and southwest directions.

Major Anions

The sequence of anion dominance in groundwater of U.A.E. has the order: $HCO_3^{-} > Cl^{-} > SO_4^{2-} > CO_3^{2-}$ in the eastern part, SO_4^{2-}, $Cl^{-} > HCO_3^{-} > CO_3^{2-}$ in the central part and $Cl^{-} > SO_4^{2-}$, $HCO_3^{-} > CO_3^{2-}$ in the western part.

High HCO3- concentrations are observed in groundwater of the northern and eastern parts of U.A.E., which are the areas receivingthe highestrainfall inthe country. The HCO3- contents decrease in the directions of groundwater flow. The fresh-groundwater mound north of Liwa is also characterized by high HCO_3^{-} contents in its center around the Well No. 135 (Fig. 1).

The SO_4^{2-} concentrations are high in theeasternandwesterncoastalplains. High SO_4^{2-} contents are also observed in Al Ain and Al Wagan groundwater. The high-sulphate groundwater may mark discharge areas of intermediate groundwater flow systems.

The Cl- ios-concentration contour map shows a pattern similar to that of the E. C., Na^{+} and K^{+}. The Cl- content is low along the Dibba-Hatta line and increases in the directions of groundwater flow.

According to Freeze and Cherry (1979), nitrate(NO_3) is the most common contaminant identified in water. The WHO (1971) recommended limits for nitrate in drinking water are 10 mg/l as nitrate nitrogen and 45 mg/l as nitrate (NO_3). Centers of high NO_3 are encountered in Wadi Al Bih, south of Dubai,AlAin,AlKhaznah, Madinat Zayed and Liwa.

Nitrate ion (NO_3-) concentration as high as 1000 mg/l in shallow groundwater of U.A.E. were measured west of Al Kaznak and at the Liwa areas. Because of the close correlation between high NO_3- contents and the locations of intensive farming, it seems that the agriculture is the main source of nitrates in shallow groundwater in U.A.E. Because of the persistent of NO_3- in oxygenated systems, the availability of abundant oxygen in the shallow horizons of the Quatemary aquifers add to the nitrate contamination problem in the country.

Water-Dissolved Salts

The main groundwater-dissolved salts in U.A.E. are $Ca(HCO_3)_2$, $Mg(HCO_3)_2$, $Na_2(SO_4)$, $CaSO_4$, $MgSO_4$, $MgCl_2$ and NaCl. The relative abundance of these salts is consistent with the prevailing hydrogeological conditions. These salts evolve in the direction of flow according to the Chebotarev series (Freeze and Cherry, 1979) and confirm the presence of different ground-water flow systems.

Groundwater in the northern limestone aquifer, the northwestern gravel aquifer, the eastern gravel aquifer and the ophiolite aquifer, which receive a relatively high rainfall, are enriched in $Ca(HCO_3)_2$ and $Mg(HCO_3)_2$ salts. The salts characterize groundwater of a local flow system. This water has a low salinity, a short residence time and a good quality.

Groundwater in the western gravel aquifer are dominated by $CaSO_4$ and $MgSO_4$ salts, which mark an intermediate groundwater flow system. The groundwater of this system is mainly brackish and of intermediate residence time.

In the sand dune aquifer which occupy the western and southern parts of U.A.E., groundwater contains $MgCl_2$ and NaCl salts indicating a regional groundwater flow system. The groundwater in this system is mainly saline and has a long residence time.

Groundwater types

Trilinear plots of the chemical analyses of water samples collected from the U.A.E. groundwater show that the ophiolite rocks are characterized by three water types; $Mg(HCO_3)_2$, $MgCl_2$ and NaCl. The $Mg(HCO_3)_2$ and $MgCl_2$ types occupy the fractures of the mountain masses, whereas the NaCl water type occurs in the wadis dissecting these mountains. These water types reflects the effect of dissolution Mgrich ophiolitic rocks. However, these waters still possess the best quality in the country.

Groundwater in the eastern gravel aquifer has an $MgCl_2$ type,whereas the groundwater in the northwestern gravel aquifer has an NaCl water type. This again reflects the effect of dissolution of Mg-rich ophiolitic rocks. The high chloride content in in the northwestern gravel aquifer indicates salt-water intrusion as a result of excessive groundwater pumping.

The western gravel aquifer shows variable water types depending on the relative proximity to the northern Oman mountains. On its eastern side, this aquifer is characterized by $Mg(HCO_3)_2$ and $Ca(HCO_3)_2$, in its central part the aquifer is characterized $CaSO_4$ and $MgSO_4$ water types and the western side of the aquifer is dominated by the NaCl water type.

The sand dune aquifer in the Liwa area is characterized by the NaCl water type. Despite its old age the low salinity of this groundwater is related to the nature of aquifer which is mainly composed of pure sand.

Water Quality

The iso-E. C. contour map (Fig. 13) shows that the groundwater in the eastern mountains and the flanking gravels is mainly fresh and can be used for all purposes. However, because of the excessive pumping, groundwater in several areas is now suffering from salt-water intrusion not only from the sea but from deeper horizons of the same aquifer and possibly from nearby sabkha deposits.

The iso-hardness contour map shows that the groundwater is very hard in the northeastern, Al Dhaid, Kalba, Al Khaznah and along the western coast (Fig. 14). Groundwater in the eastern mountains and most of the flanking gravels does not have hardness problem and can be used for domestic purposes.

The calculated Sodium Adsorption Ratios (S. A. R.) show that the groundwater in the northern and eastern parts of the country has little harmful effect on plants and soils (S. A. R. <10). Groundwater along the western coast, west Al Ain and east Liwa has high S. A. R. values (S. A. R. >26) andcanbe very harmful to plants and soils when used for irrigation (Fig. 15).

Hydrochemical Coefficients

Hydrochemical coefficient show the relative concentrations of various ions and are used to indicate the predominance of a particular ion and to define locations of salt-water intrusion.

The Ca/Mg ratio in groundwater of U.A.E. shows that Ca^{2+} is dominant over Mg^{2+} in the northern limestone aquifer, along Khatt-Al Khanah line, aroundJabal Hafit and in the sand dune aquifer.

The SO_4/Cl ratio in groundwater of U.A.E. indicates that the SO_4^{2-} is dominant over Cl~ at Suweyhan, between Dubai and Abu Dhabi and south of Liwa.

The Cl/(CO_3+HCO_3) ratio is used to evaluate salt-water intrusion, either from neighboring areas or from underlying formations. The chloride-ion (Cl-) is a dominant anion in salt water and normally occurs in small amounts in groundwater. The bicarbonate-ion (HCO_3-) is the most abundant anion in groundwater. The Cl/(CO_3+HCO_3) ratio shows that groundwater in most of the country is suffering from serious salt-water intrusion problems, except for the central part of the ophiolite aquifer.

The Na/Cl ratio is also used to indicate areas suffering from salt-water intrusion. Salt-water intrusions problems exist in Ras Al Khaimah, Al Dhaid, Diba, Kalba, Dubai - Jabal Al Dhanah, Madinat Zayed, Liwa and Al Ain areas.

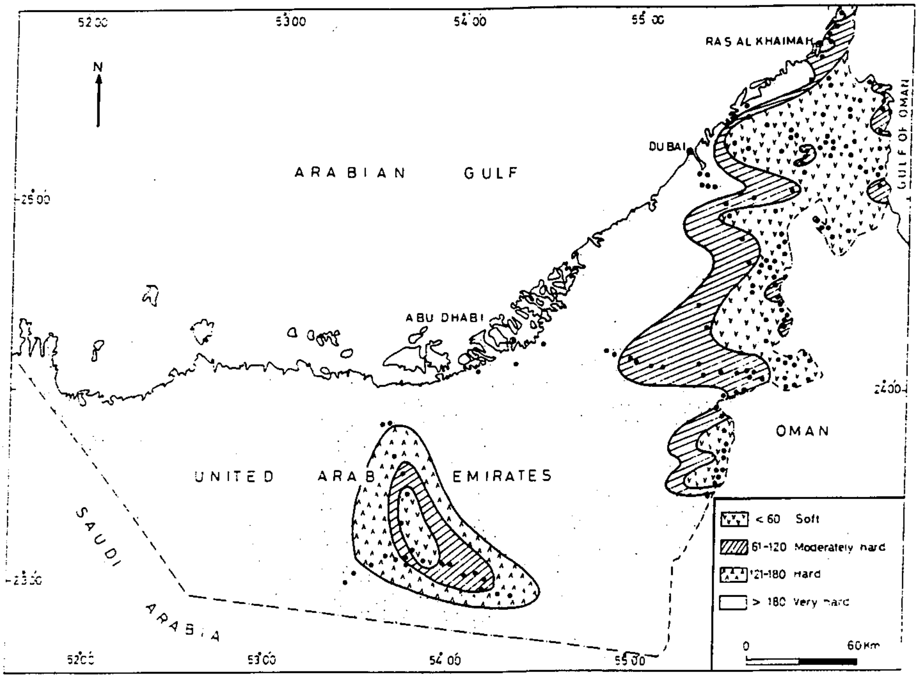

Figure 14. Calculated total hardness (mg/l) of groundwater in U. A. E. as in March 1996. Black circles represent data points.

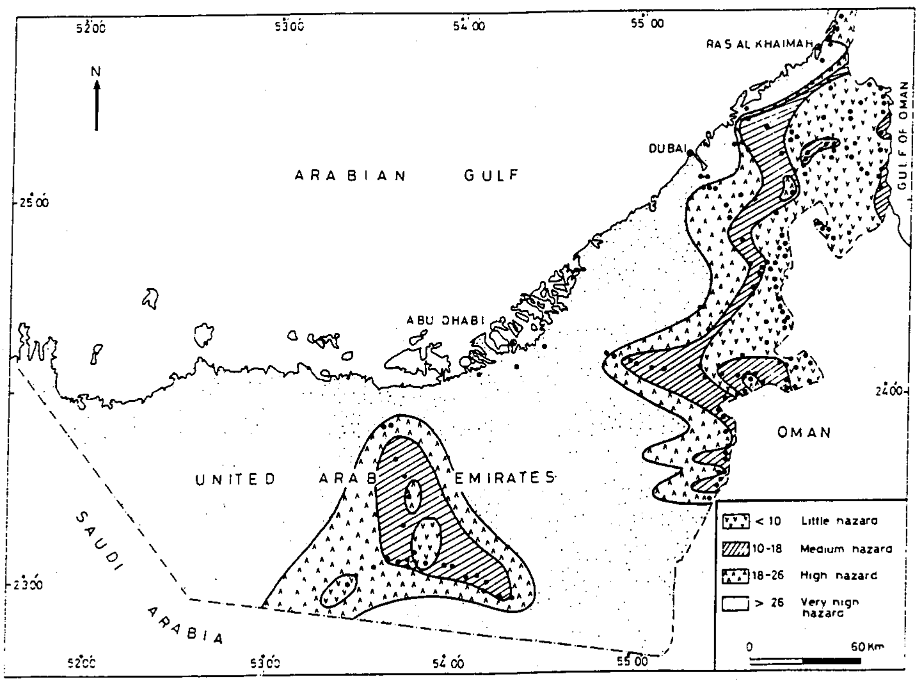

Figure 15. Calculated Sodium Adsorption Ratio (S. A. R.) of groundwater in U. A. E. as in March 1996. Black circles represent data points.

CONCLUSIONS

The mean annual rainfall in U.A.E. for the 1934-1996 period shows the presence of cycles of about 10 years during which above average rainfall occurs and can contribute to groundwater recharge.

The measured depths to groundwater are < 5 m in the Liwa, Khatt, Shaam and the eastern coast, 50-100 m in Wadi Al Bih and Al Ain areas, and >100 m in Al Dhaid area. Excessive groundwater pumping has created four major cones of depressions centered in Al Dhaid, Hatta, Al Ain and north of Liwa. These cones cause decline of groundwater levels, dryness of several shallow wells, increase of groundwater salinity and salt-water intrusion.problems.

The groundwater flow in the sand and gravel aquifers on the western side of the eastern mountains is generally from east to west and northwest between Latitudes 24° 00° and 26° 00° N and from southeast to northwest between Latitudes 22° 00° and 24° 00° N. Detailed study of groundwater flow in U.A.E. points out to the presence of local, intermediate and regional groundwater flow systems. The local system has a good quality, low salinity and HCO_3^- type water. The intermediate system has brackish, SO_4^{2-} type water. Water of the regional system is mainly saline, old and belongs to the Cl^- type.

Centers of high groundwater temperatures are observed in springs and wells of Khatt (Ras Al Khaimah), Al Dhaid (Al Sharijah), Hatta (Dubai) and south Al Wagan (Abu Dhabi) areas. These centers lie alongaNNE-SSW striking thrust fault which represents the wetern boundary of the northern Oman mountains.

The sequence of cations dominance in groundwater of U.A.E. has the order: $Mg^{2+} > Ca^{2+} > Na^+ > K^+$ in the eastern part, $Ca^{2+} > Mg^{2+} > Na^+ > K^+$ in the central part, and $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ in the western part. The sequence of anion dominance has the order: $HCO_3^- > Cl^- > SO_4^{2-} > CO_3^{2-}$ in the eastern part, SO_4^{2-}, $Cl^- > HCO_3^- > CO_3^{2-}$ in the central part and $Cl^- > SO_4^{2-}$, $HCO_3^- > CO_3^{2-}$ in the western part. The main groundwater-dissolved salts are $Ca(HCO_3)_2$ and $Mg(HCO_3)_2$, in the northern and eastern parts, $Na_2(SO_4)$, $CaSO_4$ and $MgSO_4$ in the central part and $MgCl_2$ and NaCl in the western and southwestern parts. The relative abundance of these salts is consistent with the prevailing climatic and hydrogeological conditions. The bicarbonates (HCO_3^-) are the dominant water types in the northern and eastern parts of U.A.E., sulphates (SO_4^{2-}) are the dominant water types in the central parts and chlorides (Cl^-) are the dominant water type in the western and southwestern parts. The $Cl/(CO_3+HCO_3)$ is mainly greater than one indicating that the groundwater in most of the country is suffering from serious salt-water intrusion problems, except for the central part of the ophiolite aquifer, where the $Cl/(CO_3+HCO_3)$ ratio is less than one. The Na/Cl ratio is also greater than one in Ras Al Khaimah, Al Dhaid, Diba, Kalba, Dubai - Jabal Al Dhanah, Madinat Zayed, Liwa andAl Ain, indicating salt-water intrusions problems.

The iso-electrical conductivity contour map shows that the groundwater in the eastern mountains and the flanking gravels is mainly fresh and can be used for all purposes. Groundwater is very hard in the northeastern, Al Dhaid, Kalba, Al Khaznah and along the western coast. The calculated Sodium Adsorption Ratios (S. A. R.) show that the groundwater in the northern and eastern parts of the country has little harmful effect on plants and soils, whereas the water along the western coast, west Al Ain and east Liwa has high S. A. R. values and can be very harmful to plants and soils when used for irrigation.

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Survey on Groundwater Recharge and Flow in Wadi Wurrayah

Mohammed S. Abdulla and Ahmad A. Durabi

SURVEY ON GROUNDWATER RECHARGE AND FLOW IN WADI WURRAYAH

Mohammed S. Abdulla and Ahmad A. Durabi
Ministry of Agriculture & Fisheries
United Arab Emirates

ABSTRACT

The Wadi Wurrayah Basin is located in the east coast of the U.A.E. The wadi system rises in the mountains north east into the gulf of Oman. The surface water catchment forming the basin is approximately 129 Km2. The wadi is active in terms of surface flow and during a normal wet year flows to the sea a number times. In the upreaches about 10 Km upstream there are three water falls. These waterfalls are prenial and a major source of groundwater recharge in the basin. In view of its importance as a major source of water for agriculture and domestic supplies a study has been carried to evaluate the groundwater recharge and the surface flow in the wadi Wurrayah, which is the subject of the paper.

Hydrogeology of the Geothermal Fractured-Rock Well Field at Jabal Hafit, Abu Dhabi Emirate

Mohamed A. Khalifa

HYDROGEOLOGY OF THE GEOTHERMAL FRACTURED-ROCK WELL FIELD AT JABAL HAFIT, ABU DHABI EMIRATE

Mohamed A. Khalifa
National Drilling Company
P.O. Box 15287
Al Ain, United Arab Emirates

ABSTRACT

The Ground-Water Research Project, a collaborative project of the National Drilling Company of Abu Dhabi and the U.S. Geological Survey, has evaluated the long-term potential of the ground-water resources and the water from the Mubazzarah well field. The well field is in a valley at the north end of Jabal Hafit, a highly fractured doubly plunging anticline in eastern Abu Dhabi Emirate. Fifteen wells, 90 to 200 meters in depth, produce a combined 21,000 cubic meters per day of thermal-brackish water with temperatures of 36-52 degrees Celsius, total dissolved solids concentration of about 3,900 to 6,900 milligrams per liter, and high radium-226 and radon-222 values. The thermal water is derived from fractured and cavernous limestone of middle Eocene and Paleocene age. Calculations of the geothermal gradient based on silica thermodynamic data and geologic structures associated with uplift of the Jabal indicate the depth of water circulation may exceed 2,000 meters. Well yield of as much as 850 gallons per minute are attributed to fracture permeability and dissolution. A substantial drop in yield is probable if secondary porosity features are not interconnected. Water from the Mubazzarah well field is used for a recreational spa and potentially will be used for irrigation. Water samples were analyzed for common ions, trace metals, and radioactive elements. Evaluation of the analysis by experts in the Czech Republic indicated that the water has high curative and therapeutic value because of high mineral content and temperature. Since July 1995, well discharge, ground-water levels, and specific conductance have been measured periodically in the well field. Results of the continuing investigation will be used to better understand the hydrogeologic system, the source of radioactive thermal water, and the potential effects of pumpage.

INTRODUCTION

The Ground-Water Research Project (GWRP) was initiated in 1988 as a cooperative program between the National Drilling Company (NDC) of Abu Dhabi Emirate and the United States Geological Survey (USGS). The project objectives are to evaluate the ground-water resources for the Emirate of Abu Dhabi, and to establish a hydrologic data base to be useful for future assessments of water-resources projects.

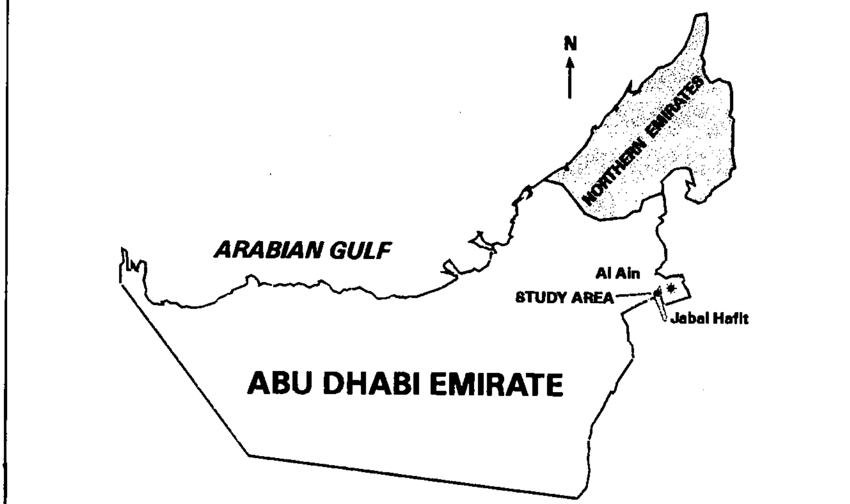
In June 1995, the Al Ain Municipality contacted the GWRP requesting a plan of study to estimate the potential long-term supply of the ground-water reservoir at Mubazzarah well field. The Mubazzarah area (figs. 1 and 2) is located in a valley about 2 kilometers long by 0.5 kilometer wide at the north end of Jabal Hafit near Al Ain. Fifteen large diameter wells have been completed in the well field, with about 10 wells capable of producing large quantities of water. Well depths range from 90 to 200 meters and yields of as much as 4,600 cubic meters per day (m3/d), or 850 gallons per minute (gal/min), are attributed to fracture permeability and dissolution. A substantial drop in yield is probable if secondary porosity features are not interconnected.

Water supplied by the well field will be used for a therapeutic spa and for recreational purposes. Measured discharge to a holding pond west of the well field has been as high as 21,000 m3/d (4,000 gal/min). The GWRP is conducting continuous monitoring of water levels and specific conductance using a data collection platform (DCP) installed on one well, and measurements of water levels, specific conductance, and discharge rates on other wells by regular field trips to the area.

GEOLOGICAL SETTING

Jabal Hafit is a doubly plunging, asymmetrical anticline, which trends north-south (fig. 3). The asymmetry of the fold is characterized by a steeply dipping to overturned eastern limb and a more gently dipping western limb. The outcrop is bounded by thrust faults, a major thrust to the west and a conjugate back thrust to the east.

The rocks that form Jabal Hafit are cut by numerous normal and near vertical faults and fractures. Faults are considered to be fracture planes or fracture surfaces along which there has been appreciable movement. The normal fault displacement of rocks at Jabal Hafit is a result of collective or differential movement along the numerous fracture planes. The normal faults and fracture pattern exposed at the outcrop strike perpendicular to the axis of the fold or



Fiqure 1. General location of the study area in Abu Dhabi Emirate.

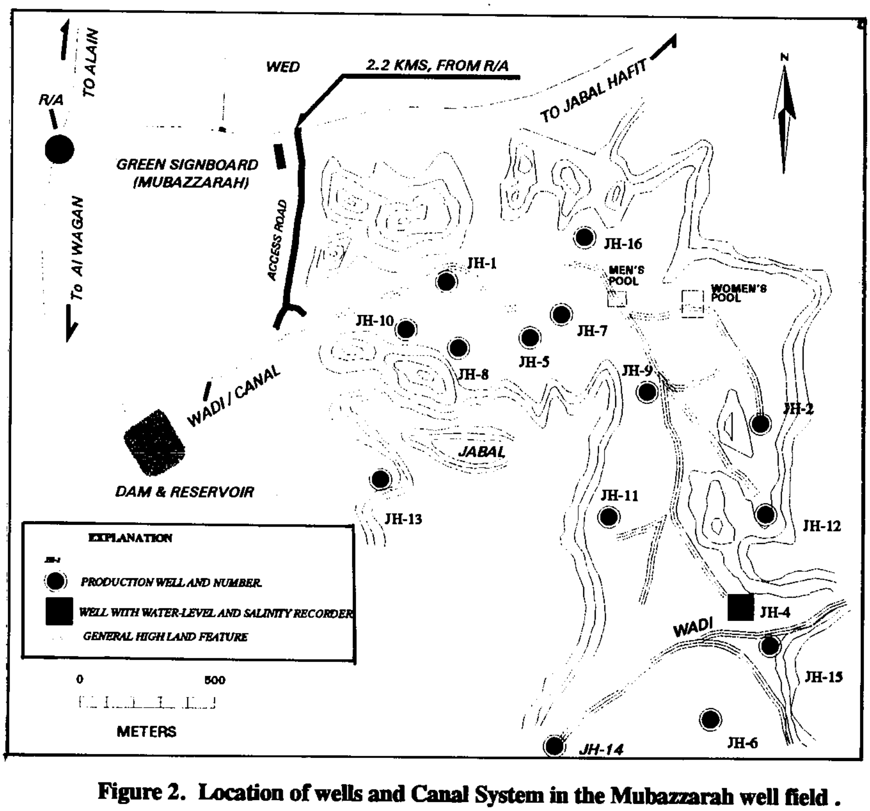


Figure 2. Location of wells and Canal System in the Mubazzarah well field.

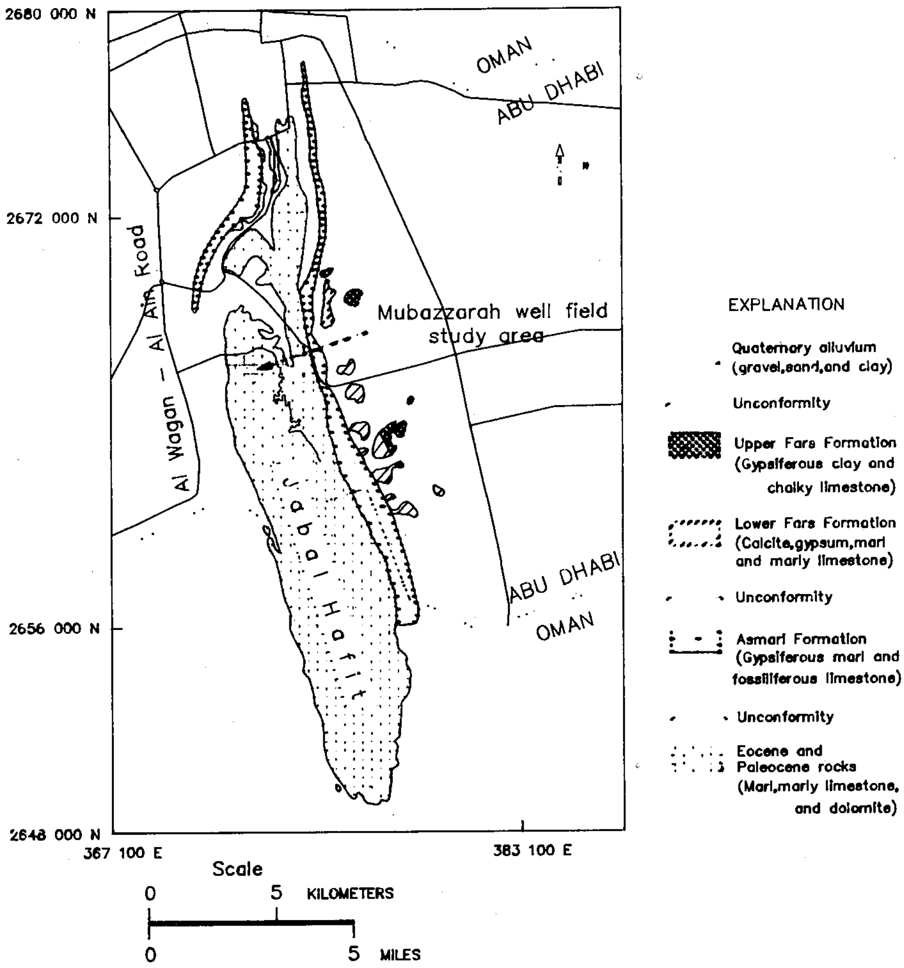


Figure 3. Surficial geology of the Jabel Hafit area (From Maddy, 1993)

form north-east and north-west — trending conjugate sets.

Because of their nearly planar nature, faults and fractures provide an heterogeneous secondary porosity in carbonate aquifers. Kastning (1977) has demonstrated that, with respect to their influence on ground-water flow and conduit enlargement, faults may have a positive, negative, or neutral effect. If faults increase permeability of the aquifer or otherwise enhance flow characteristics of the aquifer, the effect of the fault is positive. Examples of the positive influence of faults on ground-water movement include characteristically open fracture systems resulting from tensional (extensional) forces and increased rate of breakdown of cavern roofs in areas where faults intersect the caverns. Extensional, open-fracture systems typically occur parallel to the crest and perpendicular to the plunge of the anticline.

Jabal Hafit is primarily composed of interbedded carbonate and evaporite formations (fig. 3) of Lower Eocene to Miocene age. The rocks are mainly limestones and marls interbedded with gypsum and dolomite. The average thickness is about 1,500 meters, but the thickness of the water-bearing formation is significantly less.

FRACTURED LIMESTONE AQUIFER

According to Stringfield and Le Grand (1966), if thick deposits of low permeability overly a carbonate terrain, and if the carbonate was never elevated into a ground water circulation system, then little secondary porosity will be developed. On the other hand, early elevation of the carbonate into a ground-water circulation system will lead to development of secondary porosity and permeability and to partial or complete removal of the carbonate. The emergence of mature carbonate terrain relative to sea level lowers the base level for ground-water discharge, which permits meteorically derived fluids to penetrate the "elevated" terrain more deeply, thereby contributing to secondary porosity and the formation of deep-seated karst.

White (1977) proposed three conceptual models for carbonate aquifers:

1. Diffuse-flow carbonate aquifers have had little solutional activity directed toward opening large channels, these are to some extent homogeneous.

2. Free-flow aquifers receive diffuse recharge, but have well-developed solution channels along which most flow occurs. Ground-water flow in free-flow aquifers is controlled by the orientation of the bedding planes and fractures that determine the location of solutional conduits, but not by confining beds.

3. Confined-flow carbonate aquifers have solution openings in the carbonate units, but low permeability non-carbonate beds exert control over the direction of ground-water movement. This category is similar to the aquifer system in Jabal Hafit area where the marl unit capping the Eocene limestone rocks acts as the confining layer of the aquifer.

Geophysical logging of selected wells at Mubazzarah indicate the possibility of a confined-flow carbonate system. Logs include a color television inspection for well number JH-14 and a temperature-conductivity log and caliper log for wells JH-14 and JH-15. Borehole geophysical logging in well JH-4 included caliper, temperature, conductivity, and flowmeter survey. The television log of well JH-14 indicated that most of the rock consists of massive limestone and marl with very low porosity and therefore with very little prospect of producing water. The exception to this is the interval between 101 and 112 meters, which is fractured limestone. Fracture widths in this interval are as great as 9 centimeters, indicating that this interval could produce most of the water yielded by the well. The flowmeter survey for well JH-4 indicated that high-temperature water was flowing into the well from a fractured interval between 93 and 102 meters.

GROUND-WATER LEVEL FLUCTUATION

In June 1996, ground-water levels ranged between about 6 and 61 meters below land surface. Ground-water levels generally were declining throughout the wellfield. An example of declining water levels is the hydrograph for well JH-4 shown in figure 4. The water from the pumped wells flows downstream where it enters unlined pools and channels. Water levels in wells in the downstream areas generally rose, perhaps in response to recharge water percolating downward from the channels and ponds. An example of rising water levels is the hydrograph for well JH-7 shown in figure 5.

WATER QUALITY

Water samples were collected from selected wells and analyzed to evaluate the chemical and physical quality of the water and to aid in understanding the geochemical and hydrologic relationships in the aquifer system. Water samples were sent to a USGS laboratory to be analyzed and interpreted.

1. Chemical Properties:

Detailed chemical analysis was conducted on water samples collected from 8 wells in the Mubazzarah well field. The results of these analyses are shown in Table 1.

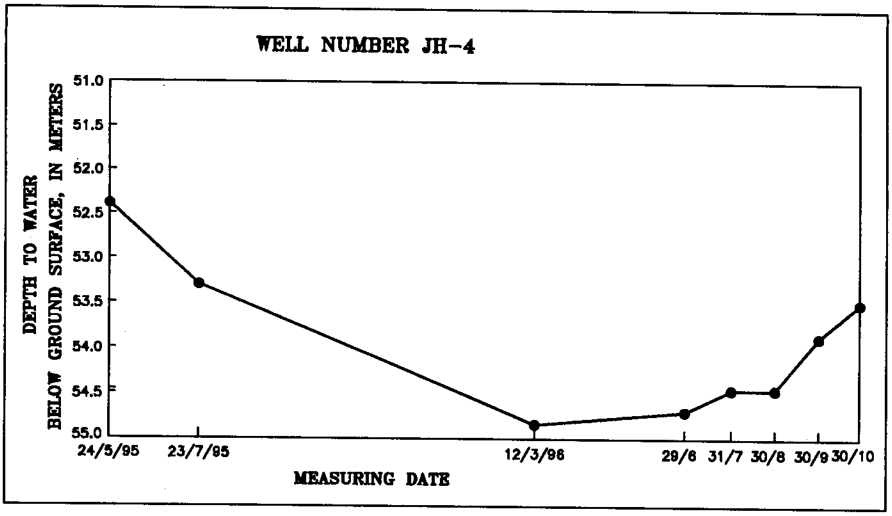


Figure 4. Hydrograph of well number JH-4 showing a decline in the water level.

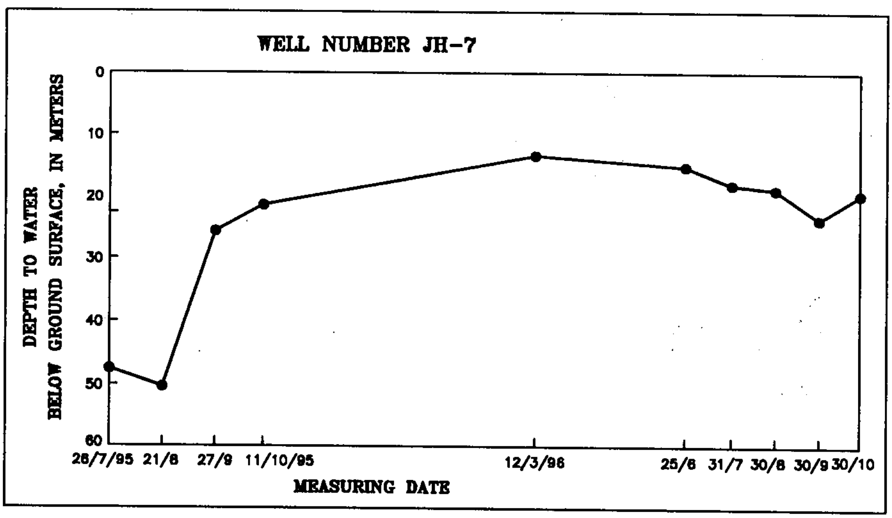
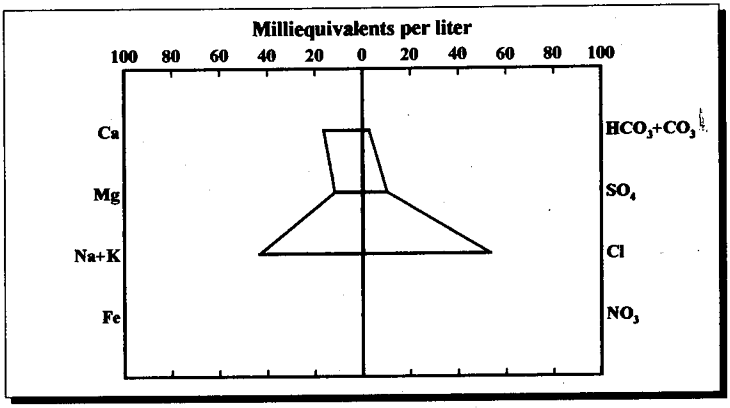


Figure 5. Hydrograph of well number JH-7 showing a rise in the water level.

Well number JH-5

(Temperature = 36.7 °C; dissolved solids = 5,860 mg/l)



Well number JH-9

(Temperature = 47 °C; dissolved solids = 6,900 mg/l)

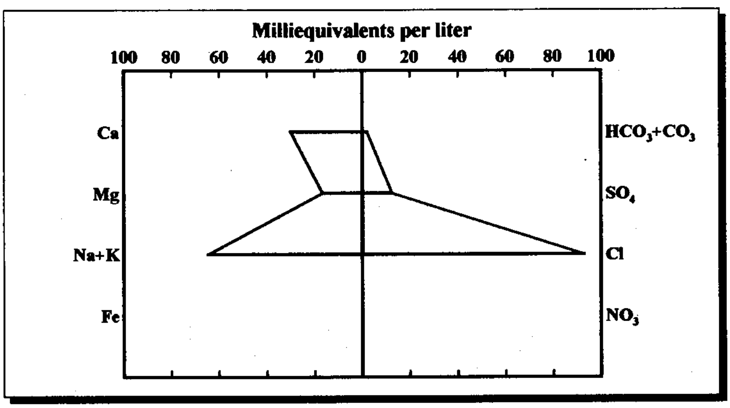


Figure 6. Relative temperatures and concentrations of major ions in water from wells JH-5 and JH-9.

Table 1.
Common-ion and trace-element concentrations in water from selected wells at the Mubazzarah well field (mg/l, millligrams per liter; meq/l, milliequivalents per liter; %, percent; µg/l, micrograms per liter; µS/cm, microSiemens per centimeter; °C, degrees Celsius)

Well No.	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	Sr mg/l	Fe mg/l	Mn mg/l	Si mg/l	HCO_3 mg/l	F mg/l	Cl mg/l	Br mg/l	NO_3 mg/l	SO_4 mg/l
JH-1	375	135	1100	35	5	0.68	0.039	11	226	.07	2000	7.9	0.81	775
JH-2	575	150	1325	50	24	0.92	0.053	14	123	2.27	3000	14	0.48	450
JH-4	575	145	1325	50	23	0.99	0.060	15	107	2.27	2950	16	0.14	500
JH-5	325	140	975	33	23	0.75	0.039	10	182	1.79	1900	7.9	1.1	500
JH-7	325	150	1075	35	30	0.87	0.039	10	198	1.79	2000	5.1	2.5	625
JH-8	425	145	1200	40	20	0.78	0.046	12	151	2.27	2500	12	0.25	550
JH-9	600	200	1450	60	29	1.06	0.067	14	122	2.41	2300	18	0.39	600
JH-10	550	175	1400	55	25	0.94	0.062	12	154	2.14	2900	14	0.54	750

Well No.	Total Cations meq/l	Total Anions meq/l	Error %	B µg/l	Ba µg/l	Cr µg/l	Cr(6+) µg/l	Zn µg/l	Cl/Br	pH	EC µS/cm	TDS mg/l	Temp. °C
JH-1	78.71	76.38	1.5	1350	117	<5	<1	235	253	7.24	7,150	4,800	37.1
JH-2	100.54	96.32	2.14	1100	171	<5	<1	28	211	7.14	8,260	5,500	49.3
JH-4	100.1	95.71	2.25	1100	174	<5	<1	375	184	7.17	9,240	6,200	51.4
JH-5	71.55	67.2	3.13	1200	142	<5	<1	165	241	7.14	5,860	3,900	36.7
JH-7	76.94	72.88	2.71	1650	134	<5	<1	500	392	7.34	6,330	4,200	37.2
JH-8	86.85	84.72	1.24	1150	115	<5	<1	235	214	7.06	7,150	4,800	37.9
JH-9	111.71	107.94	1.72	1250	184	<5	<1	32	186	7.03	10,250	6,900	47
JH-10	104.76	100.25	2.2	1500	154	<5	<1	28	201	7.08	9,550	6,400	36.5

The temperatures in thermal wells range between 36.5 and 51.4 degrees Celsius (°C). The water is generally slightly alkaline (pH 7-8), sodium-chloride rich, and has a range in total dissolved solids (TDS) concentration between 3,900 and 6,900 mg/l. Results of chemical analyses indicate two geochemically different waters. The first type of water is relatively low in temperature and TDS, represented by well JH-5. The second type of water is relatively high in temperature and TDS, represented by well JH-9 (Table 1). Stiff diagrams of water from these wells show that sodium is the dominant cation, while chloride is the dominant anion (fig. 6).

Saline water with a TDS concentration greater than 15,000 mg/l is known to underlie Al Ain area (Maddy, 1993). The high chloride concentration at Mubazzarah well field may be an indication of upwelling saltwater from a deep source. Magnesium and sulfate may be derived from dolomite, gypsum, and anhydrite of the carbonate and evaporite rocks in Jabal Hafit. The waters have been in contact with limestone and are assumed to be near saturation with respect to calcite.

2. Radiochemical Analysis:

The lower part of the Jabal Hafit lithologic succession consists of Middle Eocene limestone. This limestone typically has a black organic precipitate along joints and bedding planes. The precipitate contains about 21 parts per million of uranium (El-Shami, 1990). Uranium is the parent element in a long series of radioactive decay that creates daughter elements including radium and radon. Just as uranium is present in rocks so are radon and radium. High content of radium and radon occurred in the water samples from Mubazzarah well field (Table 2). Radon is a gas produced by the radioactive decay of the element radium. Radon itself is radioactive because it also decays, losing an alpha particle and forming the element polonium. Because radon is a gas it has much greater mobility than uranium and radium, which are fixed in the solid matter in rocks. Therefore, radon moves more readily through permeable formations and fractured rocks and moves slower in water-saturated rocks than in dry rocks or in air. Thus radon travels shorter distances in saturated rocks than in dry rocks before it decays. If the water was exposed to the atmosphere it will lose most of its gas content of radon, because it will escape into the air.

The maximum contaminant level recommended by the U.S. Environmental Protection Agency (1991) for radium-226 in drinking water is 5 picocuries per liter. No maximum contaminant level has been set for radon-222. Because the salinity of the water produced from Mubazzarah well field exceeds the secondary maximum contaminant level for drinking water (TDS over 500 mg/l) the water is not suitable for consumption but no risk is associated with using this water as

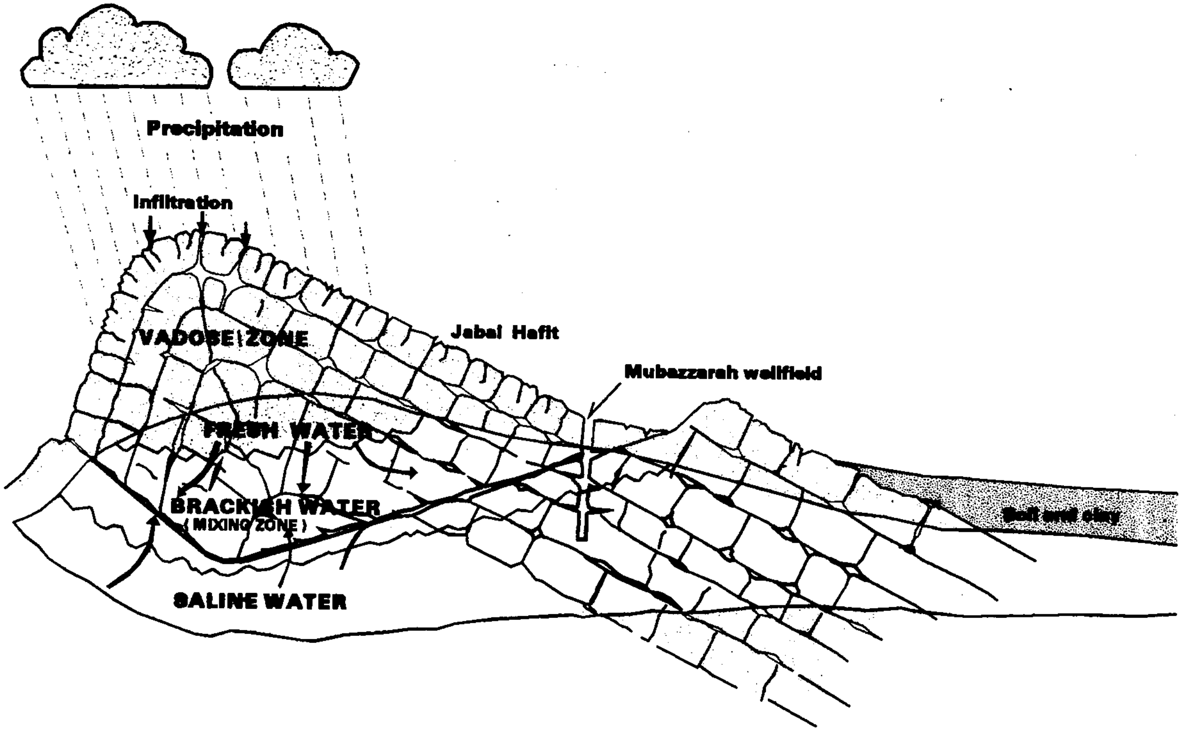


Figure 7. Diagrammatic cross section of Jabal Hafit showing conceptual model of recharge and discharge in the aquifer system .

a recreational spa or for irrigation (Polytechna, 1996).

Table 2.
Radioactive element and environmental isotope concentrations in water from Mubazzarah well field (pCi/l, picocuries per liter; µg/l, micrograms per liter; TU, tritium units)

Well number	Radium-226 (^{226}Ra) (pCi/l)	Radon-222 (^{222}Ra) (pCi/l)	Uranium (^{238}U) (µg/l)	Tritium[1] (^{3}H) (TU)	Deuterium (^{3}H) per mil	Oxygen[2] (^{18}O) per mil
JH- 1	3.2	489	3.0	0.89	- 8.57	-2.33
JH- 2	457	2836	--	.30	-10.10	-2.11
JH- 4	428	1743	0.5	.55	-10.70	-2.08
JH- 5	1.3	1698	2.1	1.39	- 8.13	-2.20
JH- 7	.9	2064	--	.45	- 8.34	-2.43
JH- 8	7.2	1557	--	.85	- 9.86	-2.16
JH- 9	349	2399	1.0	.20	-10.99	-2.01
JH-10	81	6063	--	.78	-11.64	-2.16
Channel[3]	--	1189	--	--	--	--

1 Analytical error in tritium measurement was reported as + or -0.26 TU

2 $\delta^{18}O$ is defined by

$$\delta^{18}O = \frac{(^{18}O/^{16}O)\ \text{sample} - (^{18}O/^{16}O)\ \text{standard}}{(^{18}O/^{16}O)\ \text{standard}} \times 1000$$

$\delta^{18}O$ represents the relative difference in parts per thousand [per mil (‰)] between the ratio in a sample and the ratio in a standard. The same analogy holds for the deuterium calculation.

3 Open-channel flow; collected 200 meters from well JH-2.

3. Environmental Isotopes:

Selected water samples were also analyzed for environmental isotopes including tritium, deuterium, and oxygen-18. Tritium is an indicator of recent recharge and deuterium and oxygen-18 can provide clues about the genesis and flow path of ground water.

Of the eight tritium analyses presented in Table 2, only samples from wells JH-2 and JH-9, could be said to contain no tritium. Because the other six samples are above zero TU, it is construed that at least part of the water pumped from Mubazzarah well field is recent recharge.

Deuterium and oxygen-18 are expressed as delta values, which represent the ratios $^2H/^1H$ and $^{18}O/^{16}O$ compared to the ratios in Vienna Standard Mean Ocean Water (VSMOW). Negative values represent isotopically light water with respect to VSMOW and positive values represent isotopically heavy water with respect to VSMOW. The values listed in Table 2 are isotopically light relative to other groundwater samples in the area, which may reflect recharge on the elevated jabal.

GEOTHERMAL NATURE OF THE AQUIFER

On a global scale the earth's thermal regime involves the flow of heat from the deeper layers of the planet towards it's surface. The geothermal gradient that gives evidence of this heat-flow regime has been widely measured by geophysicists involved in terrestrial heat-flow studies. On average, the temperature increases approximately 1°C for each 40 meters of depth.

Chemical analyses including silica from Mubazzarah well field was entered into a program to calculate the temperatures of the geothermal reservoir based upon the departure of silica from thermodynamic equilibrium with quartz - "the quartz geothermometer". The maximum water temperatures calculated by the computer program ranged between about 67°C and 83°C (Table 3). Assuming a normal geothermal gradient of 1°C per 40 meters of depth (i.e. no magma at depth), and an average annual surface temperature of 30°C, the depth of circulation of the ground water was calculated to be between 1,500 and 2,100 meters [example: (83°-30°) X 40 = 2,120].

Table 3.
Water-sample temperature and calculated temperature based on the quartz geothermometer (°C, degrees Celsius)

Low Temperature			High Temperature		
Well number	Temperature (°C)	Calculated temperature (°C)	Well number	Sample temperature (°C)	Calculated temperature (°C)
JH-1	37.1	70.5	JH- 2	49.3	80.5
JH-5	36.7	66.6	JH- 4	51.4	83.3
JH-7	37.2	66.8	JH- 9	47.0	80.8
JH-8	37.9	74.2	JH-10	36.5	74.4

POTENTIAL USES OF GROUND WATER

Because of its high mineral content and high temperature, the water from the Mubazzarah well field should be curative and therapeutic (Polytechna 1996). The Emirate has a plan to construct a spa resort that uses this water to benefit its citizens and visitors. The water may also be used for irrigation of salt-tolerant forest plantings. However, it is not suitable for drinking because of the high TDS concentration.

CONCLUSIONS

Over geologic time, relatively large amounts of rain have fallen on the limestone of Jabal Hafit anticline. As the water dissolved the carbonate rocks of the jabal, it increased the pore space and permeability. The rocks of the jabal are relatively permeable owing to the fissures, faults, and joints. Consequently, infiltration is relatively high and evaporation and runoff are limited. In areas of folded carbonate rocks, like the Jabal Hafit anticline, zones of fracture and solution enlargement are commonly located along the crest of the anticline and to a lesser extent in synclinal troughs.

Wells that produce water with relatively high temperature and specific conductance are located close to the fold axis of the jabal as compared to wells that produce cooler and fresher water which are located further from the axis. Deep fractures may act as conduits to bring thermal and saline water close to the surface before it cools or becomes diluted.

Dissolution of limestone forms a karst aquifer system, characterized by solution channels and caves. Figure 7 shows a conceptual model of the three water-bearing zones in the Jabal Hafit area:

1) a fresh water zone, replenished by meteoric water;

2) a mixing zone where fresh water mixes with brackish water, and

3) a deep saline water zone.

The source of the water may be either meteoric water that rises by hydraulic pressure after having descended to a great depth or saline water that ascends due to gas pressure or thermal gradient. The conceptual model of the Jabal Hafit karst, supports a mixture of the two different sources. The flux of fresh recharge water through the jabal may be greater than the lateral or upward flow of saline water into the conduits. Therefore, the result is a water in the mixing zone that is brackish. The water in the conduits is heated by normal geothermal gradient at a depth of approximately 2,000 meters below the surrounding land (3,000 meters below the jabal). The conduits bring the mixed water to the base of the clastic aquifer where it enters the shallow regional flow system. The aquifer water cools to near the ambient aquifer temperature, and becomes even more dilute.

This conceptual model is supported by hydrogen (deuterium) and oxygen-18 isotopic data in ground-water samples from the Mubazzarah well field. These isotopes are relatively light compared to other ground-water samples in the surrounding area, suggesting local recharge on the elevated jabal. The solute composition of water from the sampled wells suggests mixing of deep basin saline water with calcium carbonate saturated ground water created by the dissolution of limestone. The high content of radium suggests its contact with limestone. Tritium levels in the water samples are larger than would be expected by natural subsurface production from radium or uranium. The tritium levels, while relatively low, still indicate the presence of some younger water which may indicate rapid circulation and mixing with recent local recharge on the top of the jabal.

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A New Isotope Water Line for Northern Oman

Phillip G. Macumber, J. Mohamed Niwas, Alia Al Abadi and Rohitha Seneviranine

A NEW ISOTOPIC WATER LINE FOR NORTHERN OMAN

Phillip G. Macumber, J. Mohamed Niwas, Alia Al Abadi and Rohitha Seneviratne
Ministry of Water Resources
Sultanate of Oman

ABSTRACT

The relationship between the stable isotopes deuterium and oxygen-18 for precipitation across the central parts of northern Oman (Jebel Akhdar and the Al Batinah coastal plain) is $\delta D = 5.1\ \delta^{18}O + 8$; this is very similar to that previously obtained from Bahrain by Gibb (1976). A new groundwater data set taken from aflaj and springs on and adjacent to the Jebel Akhdar/Saiq Plateau of northern Oman provides a groundwater derived water line - $\delta D = 5.1\ \delta^{18}O + 3$ ($R^2 = 0.92$) referred to here as the Akhdar Line. The most depleted isotopes in north central Oman groundwater and precipitation show some departures from the above principal trend lines towards that of the GMWL along which modem day central Oman groundwaters fall, suggesting an additional (southern?) source of precipitation..

In the rainfall records for northern Oman there is no significant depletion of δD or $\delta^{18}O$ with altitude, which is contrary to the situation found in the groundwater data. The most depleted groundwater ($\delta D < -10$; $\delta^{18}O < -3$) occurs in the high altitude eastern areas of Jebel Akhdar and its north facing upper catchments. A plume of isotopically depleted groundwater originating in the high limestone areas of the Jebel Akhdar and Jebel Nakhl passes northwards through a gap in the ophiolites at Nakhl, across the Al Batinah coastal plain. This plume has high Ca/Mg ratios relative to Al Batinah groundwaters draining adjacent ophiolitic catchments, attesting further to the limestone source areas on Jebel Akhdar.

INTRODUCTION

This paper stems from part of a larger study of the relationship between the groundwater systems on the Jebel Akhdar of northern Oman and the adjacent Al Batinah coastal plain and interior plains. The Jebel Akhdar region is part of the northern Oman mountains, a high mountain range paralleling the coast, which rises to 3000 m. At the eastern limits of the Jebel Akhdar, the high mountains extend north easterly as the Jabal Nakhl (Fig. 1) . The Jebel Akhdar is essentially a large anticlinal structure of outcropping Permian to Cretaceous sediments - the Hajar Super Group, consisting mainly of limestones and dolomites. The anticline is strongly incised on its northern flanks to produce large depressions, and exposing older pre-Permian (Late Proterozoic or Infracambrian) sediments and volcanics in the eroded core of the anticline. The central Saiq Plateau cut principally across the Hajar Super Group lies at an elevation of 2000 m.

The Jebel Akhdar is flanked by ophiolites of the Samail nappe and sediments of the Hawasina nappes. To the north is the Al Batinah coastal plain, while southwards, the wadis drain towards the arid interior. The eastern limits of Jebel Akhdar are formed by the Samail Basin, eroded into ophiolitic sequences of the Samail nappe.

Oman is arid with rainfall generally about 100 mm on the plains but rising to over 300 mm on the higher parts of Jebel Akhdar. The Jebel Akdar forms an east-west divide with drainage passing northwards towards the coastal plain and southwards to the interior.

STABLE ISOTOPES IN THE RAINFALL AND GROUNDWATER IN OMAN - PREVIOUS WORK

A number of rainfall samples from Oman have been analysed for stable isotopes (Gibb, 1976; Cansult, 1986; Stanger, 1986; JICA 1987; Clark et al., 1987; Wushiki, 1991; Macumber, 1995; and Macumber et al., 1995,). The earliest significant work in Oman was carried out by Gibb (1976) and a comprehensive treatise on isotopes across Oman was produced by Cansult (1986) for the PAWR. Other significant works were those of JICA (1986) and Stanger (1986). Wushiki (1991) sampled precipitation from three regions northern Oman, southern Oman and the Yemen. The northern Oman rainfall data came from Saiq (1800 m) on the Saiq Plateau, while the southern Oman samples came from 2 stations - one on the Salalah coastal plain and the other near the top of Qairoon Hairitti (ca 850 m a.s.l.) on the top ofthe Jebel Qara.

The Cansult study covered all of Oman, and this study showed that the isotopic character of regional (fossil) groundwater in the Dhofar Region of southern Oman lay close and parallel to the GMWL. The source of the groundwater was rainfall on the plains and mountains of southern Oman during the Pleistocene Period. More recent collection of rainfall/runoff samples during the passage of tropical cyclone A6-O in 1992 across the Al Wusta Region of central Oman in 1992, showed that modern cyclonic rainfall also fell along the GMWL (Macumber, et al., 1995). This conclusion was reinforced following a study of the origin and character of modern day freshwater lenses overlying the otherwise saline regional groundwater systems of hyper-arid central Oman (Macumber, 1995; Macumber 1996). In the lenses, very fresh (350 mg/l to 150 mg/l) groundwater unsaturated with HCO_3, occurs within a Tertiary limestone aquifer. The isotopic composition of this modern groundwater, derived from cyclonic and frontal precipitation, lies along GMWL (Fig. 2)

RAINFALL IN NORTHERN OMAN

The overall pattern for isotopic composition of northern Oman rainfall, runoff and groundwater is shown in Figure 3. Here, the groundwater data lies towards the depleted end of the rainfall data, while the runoff data lies partially outside the rainfall field. As noted by Cansult (1986), the most striking feature of the $\delta D/\delta^{18}O$ relationship in the rainfall is its non-linearity (Fig. 3c). This was attributed to evaporation occurring during rain-out. The resulting isotopic character of the rainfall departs markedly from the Global Meteoric Water Line (GMWL) and does not readily fit previously established meteoric water lines such as the GMWL, the Mediterranean meteoric water line or the IAEA's (International Atomic Energy Agency) Bahrain meteoric water line listed below

$\delta D = 8.0\ \delta^{18}O + 10$	GMWL (Craig, 1961)
$\delta D = 8.0\ \delta^{18}O + 22$	Mediterranean Water Line (Bortolami et al., 1979)
$\delta D = 6.3\ \delta^{18}O + 11.6$	Bahrain Water Line (IAEA)

It is, however, most like an earlier Bahrain Meteoric Water Line produced by Gibb (1976) based on Bahrain rainfall from 1961 to 1969.

$\delta D = 4.9\ \delta^{18}O + 9.7$ Bahrain Water Line (Gibb, 1976)

The explanation by Gibb (1976) for the low gradient (4.9) of his Bahrain Water Line is that evaporation during rainout effected the isotopic composition. Noting that there is little recharge in cases where there is less than 20 mm rainfall, and that evaporation can significantly modify the isotopic character of low intensity events, the Cansult (1986) proposed a meteoric water line for northern Oman based on a modified rainfall data set. The relationship expressed by Cansult's northern Oman meteoric water line is

$$\delta D = 7.5\ \delta^{18}0 + 16.1$$

However for the unmodified data set, the relationship between δD and $\delta^{18}O$ which most closely represents the overall character of the precipitation, whatever its contribution to groundwater recharge, is:

$$\delta D = 5.0\ \delta^{18}O + 8.1 \qquad (R^2 = 0.85)$$

More recently, Wushiki (1991) provided a further rainfall data set from the Saiq Plateau, and a 'best fit' trend line (Fig. 4) for northern Oman, which includes this additional data, gives a similar line to that derived from the earlier unmodified precipitation data set -

$$\delta D = 5.1\ \delta^{18}O + 8.0 \qquad (R^2 = 0.86).$$

This composite line has one of the lowest gradient of any previously derived meteoric water lines in Arabia and is very similar to the original Gibb (1976) Bahrain line (above), indicating that from an isotopic perspective, similar precipitation sources and rainfall processes occur in northern Oman as occurs at Bahrain. Taken alone, the $\delta D/\delta^{18}O$ rainfall data set from Saiq (Fig. 5) incorporating values from Wushiki, (1990), Cansult (1986) and Stanger (1987) gives the relationship:

$$\delta D = 4.9\ \delta^{18}O + 9.0 \qquad \text{(all Saiq rainfall data)}$$

This relationship is almost identical to Gibb's (1976) Bahrain MWL

$$\delta D = 4.9\ \delta^{18}O + 9.7$$

There is therefore a uniformity for the $\delta D/\ \delta^{18}O$ relationship in precipitation, from sea level at Bahrain to the high altitude Saiq Plateau, and more generally to northern Oman, whatever the atmospheric processes effecting that relationship

Despite being collected at Saiq (elevation 2000 m), the rainfall data set does not show any special pattern indicative of high altitude isotope depletion, or significant depletion with rainfall amount. For instance, the rainfall data set collected from the Saiq Road study by Stanger (1986) was relatively enriched, with all δD values being positive. Yet significant depletion is recorded in higher altitude groundwaters (Nazareth and Ravenscroft, 1996, Cansult, 1996) and has been noted in rainfall in northern Oman (Clark, 1987).

STABLE ISOTOPES IN THE GROUNDWATER SYSTEMS OF NORTHERN OMAN

The Akhdar Water Line

For northern Oman, the isotopic compositions of rainwater, surface water (runoff) and groundwater show limited overlaps in their respective fields. The groundwater field is fairly tightly contained within a restricted field towards the depleted end of the rainfall data set (Fig. 3a, 3b and 3c) suggesting that the smaller rainfall events have little impact on recharge - the basis for the modified Cansult (1986) line. The small amount of runoff data lies largely outside the rainfall field. As a consequence, the rainfall-based northern Oman meteoric water line established by Cansult (1986) has proved of very limited value in groundwater studies. In order to obtain a more useful parameter for use in groundwater studies, it was considered that a water line based on the groundwater systems was more appropriate than the rainfall data. Given that there is a general integration within the aquifers of a more diverse range of recharge isotopic values, groundwater isotope values represent long term averages of the recharge waters, whatever the rainfall character.

The Jebel Akhdar occupies the uppermost parts of the flow system and receives the highest annual rainfall in northern Oman. For this purpose it was considered that the low salinity groundwater in the higher elevation Jebel Akhdar region and its surroundings high level catchments, would best reflect the isotopic character of rainfall which recharges the groundwater systems in the upper parts of the flow path. It is clearly an appropriate starting point to examine groundwater interactions between the Jebel Akhdar aquifers and those of the surrounding plains.

Accordingly, fifty samples were collected from afiaj and springs of Jebel Akhdar at both high altitude and emerging at plain level at the foot of the Jebel. The $\delta D/\delta^{18}O$ relationship was found to give a good linear fit with $R^2 = 0.92$. This groundwater data therefore provides a new groundwater derived water line (Akhdar Water Line - Fig. 6) for use in northern Oman groundwater studies.

The relationship is:

$\delta D = 5.1\ \delta^{18}O + 3$ $R^2 = 0.92$ (Akhdar Water Line)

It is noteworthy that the slope of this line is the same as that of the 'best fit' meteoric water line derived from the northern Oman (Jebel Akhdar/Al Batinah) rainfall data, but there is a 5 unit deuterium deficit.

$\delta D = 5.1\ \delta^{18}O + 8$ $R^2 = 0.86$ (Meteoric Best Fit)

A similar deuterium deficit to that provided by the Akhdar Line was previously noted by Gibb (1976) with his limited limestone spring samples.

Given that the groundwater based Akhdar Line is a derivative of the rainfall responsible for the "meteoric best fit" line, then the simplest explanations is that there is overall a consistent evaporative effect resulting in a 5 unit δD deficit. Alternatively, deuterium shifts can be caused by interaction with $\delta^{18}O$ in rocks, however this is normally at elevated temperatures. Whatever the case, a full explanation for the rainfall/groundwater relationship, is beyond the scope of this paper and instead focus is primarily on the acceptance of the groundwater based Akhdar Water Line, to provides an empirical framework with which to examine the evolution and differences between groundwaters in northern Oman. More specifically it provides a basis for examining the relationship between groundwater on Jebel Akhdar and its catchments, and groundwater on the adjacent coastal and inland plains.

Of special note is the observations that in the cases of both northern Oman rainfall and groundwater, the isotopic relationship between δD and δ180 occurring towards the depleted end of the respective water lines, shows a degree of duality, with some samples showing departures from the principal trend lines towards that of the GMWL. These departures probably reflect a northerly intrusion of rainfall patterns normally occurring across central and southern Oman. Given that central Oman groundwater is strongly depleted ($\delta^{18}O$ mostly ranging from -2 to -6 o/oo), such effects would only appear towards the isotopically depleted end of the trend lines.

Using the Akhdar Line as a framework, comparisons have been made with other previously obtained isotopic data sets from northern Oman for a range of groundwater types from various catchments. This provides an important indication of the nature of the relationships between the groundwater of Jebel Akhdar, and that in its upper and lower catchments on the Jebel and on the plains. For instance when the earlier Cansult (1986) isotope data for Jebel Akhdar/ Saiq Plateau and the surrounding lower area at Tanuf is added to th e Akhdar Water Line, it falls comfortably within the Akhdar field with only a slight change in correlation coefficient (R^2 = 0 90).

A plot of $\delta D/\delta^{18}O$ for groundwater data from the upper (limestone) catchments of Jebel Akhdar shows that the groundwater from the Saiq Plateau and the northern Jebel Akhdar catchments lies towards the depleted end of the Akhdar Line, while that from the southern catchments is comparatively enriched Iying towards the positive end of the Akhdar Line (Fig. 7). This difference is brought out even more in the distribution maps of δD and $\delta^{18}O$ on the Jebel Akhdar and across the Al Batinah coastal plain (Figs. 8 and 9).

DISTRIBUTION OF ISOTOPICALLY

Depleted Groundwater The general distribution of isotopically depleted groundwater (Figs. 8 and 9) occurs in a west to east belt across the northern catchments of the Jebel Akhdar and Jebel Nakhl to the Saiq Plateau, and then extending in a plume down the Wadi Al Maawil catchment, across the Al Batinah coastal plain to the coast. Within the Jebel Akhdar/Jebel Nakhl, the principal aquifers are limestones and dolomites of the Hajah Super Group. In the east, the depleted groundwater coincides with the highest parts of the jebel, however further west (except in the very far western parts of the area), this is not the case, and instead the most depleted groundwater coincides with the northern upper catchments.

The rainfall data does not indicate that significantly different rainfall occurs either side of the Jebel. Indeed, the close similarity between the Bahrain Water Line and the Saiq rainfall data indicates quite the opposite. However, the more enriched character of springs and aflaj at Hamra, Tanuf, Birket Al Mauz etc., which immediately abut high altitude areas to the north, shows that the latter areas are not providing depleted groundwater. Instead, the pattern of isotopically depleted groundwater extends within the limestone sequences, northwards towards the Al Batinah coastal plain. For instance, northwards groundwater flow is seen in high altitude springs emerging at Hijar, Ghubra, Qarrah and Bidayah in the Wadi Sabt at the head ofthe Gubrah Bowl which have $\delta^{18}O$ values ranging from -4.89 to 3.76 o/oo and δD values from -28.9 to -16.2 o/oo. There is very little tritium in these springs indicating an age of more than 35 years. It has been long recognized that the springs must be recharged from even higher areas on the Jebel Akhdar, and the low isotopic values occurring in springs and aflaj on the high level Saiq Plateau immediately to the south, confirm this point. Further down the wadi, values increase indicating lower albeit mid-altitude recharge (Cansult, 1986).

While the Gubrah Bowl springs occur at high altitude at the head of the catchment, similarly depleted groundwaters emerge as low altitude springs at the foot of the Jebel in the Samail Basin to the east. Again, the source of the springs is clearly high altitude precipitation on the adjacent Saiq Plateau. For example, Hammam Aflaj from the Sayjah spring (-4.1 $\delta^{18}O$ and -18.6 δD), and the Falaj Saad from the Hayl spring (3.7 $\delta^{18}O$ and 9.8 δD). By contrast, further west along the catchment divide, there is less-depleted groundwater and the low level springs at Tanuf, Hamra etc. are likewise less-depleted.

The source of the depleted groundwater passing northwards down Wadi Al Maawil is clearly the high limestone regions of the eastern Jebel Akhdar and Jebel Nakhl. However, any northwards course taken by depleted groundwaters from the Saiq Plateau must bypass the Gubrah Bowl where low permeability Mistal Formation outcrops across the Wadi Sabt catchment. Hajar Super Group limestone is continuous along the eastern flanks of the Gubrah Bowl, and a number of samples come from limestone areas of the Jebel Nakhl to the NNE of the Bowl showing isotopically depleted groundwater flow from this source.

A number of major NNE trending faults cross the Gubrah Bowl parallel to the suggested flow path and occur also in the adjacent limestone further east. Groundwater movement along major bedrock structures is well documented in the Jebel Akhdar region and this process is responsible for the presence of isotopically depleted springs in the adjacent Samail Basin. While, the structural pattern within the Jebel Akhdar plays an important role in groundwater movement, there are clear indicators that aquifers within the pre-Permian basement are also important in groundwater movement in the northern Jebel Akhdar catchments. While many aflaj are sourced in these sediments, the full significance of the pre-Permian aquifers is yet to be determined.

AL BATINAH COASTAL PLAIN

Across the Al Batinah coastal plain $\delta^{18}O$ and δD values commonly show mild to significant enrichment. However, extending down the Wadi Al Maawil catchment from the Jebel Akhdar/Jebel Nakhl onto the Al Batinah coastal plain, there is an elongated zone of isotopically depleted groundwater which passes northwards into the Barka area towards the coast. At the coast isotopic values rise in response to mixing with intruded seawater. The zone extends outwards from the limestone catchments of the Jebel Akhdar/Jebel. By comparison with the ophiolite, the limestone aquifer provides a preferred pathway for the northwards migration of depleted groundwater from the upper catchments of the Jebel.

While the distribution of isotopically depleted groundwater is easily understood in the case of rainfall on the high altitude Jebel Akhdar, the zone of depleted groundwater extending across the Al Batinah coastal plain towards Barka is clearly not a rainfall nor runoff phenomenon but a groundwater flow feature. Indeed, the path taken does not coincide with the present active wadi course of Wadis Al Maawil and Taww but instead lies between them. That is, isotopically depleted groundwater contained within the limestone sequences of the Jebel Akhdar passes preferentially downbasin from the highland areas via the gap between the ophiolites onto and across the Al Batinah coastal plain.

The course taken is directly across the deepest part of the Al Batinah coastal plain denoted by the JICA work and more recent MWR drilling (the 21 Series bores), and referred to as the Al Maawil Trough. The eastern limits of preferential groundwater flow is probably determined by the basement fault which marks the eastern limits of the structure. Near coastal groundwater discharge may occur in the sabkha areas east of A'Suwadi, which lies downbasin from the western parts of the plume.

A northwards pathway for depleted groundwaters derived from the higher altitude limestone Jebel Akhdar catchments was previously noted by Cansult (1986) who observed that groundwater in the deeper RE3 and RE4 bores was derived from areas with elevations greater than 1200 m. No tritium was present and an age of about 5000 years was obtained from the RE4 bore.

In the lower coastal plain, a number of 100 m deep bores were recently (1996) drilled in a line parallel to the coast to establish a sea water monitoring system. Sampling from close (5m) intervals shows that throughout the 100 m sections, the Ca/Mg ratios of bores within the path of the plume were by far the highest of any across the remainder of the section line. The lower Ca/Mg ratios more commonly found on the coastal plain reflect a significant Mg contribution from upbasin ophiolitic catchments.

AL KHAWD FAN

The Al Khawd Fan on the Wadi Samail drains the low altitude Samail Basin and has one of the largest catchments of the northern flowing wadis which flow to the coastal plain to the sea. The catchment is composed predominantly of ophiolites, but bounded to the east and west by limestone and shale sequences of the Hajar Super Group. Before reaching the coastal plain the Wadi Samail flows through a narrow gorge in the ophiolite which forms a barrier separating the large upper catchment from the relatively small coastal plain formed by the Al Khawd fan. The Al Khawd fan is intruded by sea water which extends at depth to about 6 km inland from the coast almost reaching the site of the Al Khawd recharge dam which lies immediately upbasin of the Seeb and Al Khawd well fields. Groundwater recharge to the Al Khawd fan is by flood runoff from the upper catchment and probably by groundwater flow through the ophiolite barrier.

STABLE ISOTOPES, AL KHAWD FAN

Fig. 10 shows the relationship between $\delta^{18}O$ and δD within the groundwater of the Al Khawd fan, the Akhdar Water Line and GMWL. The presence of intruded seawater is clearly shown in the stable isotopes which occupy a field lying below the Akhdar Water Line and mostly within the zone of positive values of $\delta^{18}O$ and δD. The majority of the freshwater analysis extend in a broad zone straddling the Akhdar line which passes into the seawater field at its enriched end, probably reflecting seawater intermixing.

By comparison with the Jebel Akhdar analyses, the groundwaters are significantly more enriched in stable isotopes, perhaps reflecting recharge in part by flood runoff from the extensive Samail Basin. Of the fresh water samples, those from the uppermost areas of the fan upstream of the recharge dam are the most isotopically enriched and occupy an area adjacent to the sea water field. A suggested explanation is that at the uppermost area of the fan, runoff from the Al Khawd Basin is most likely to be recharged first. Only the bigger recharge events are likely to impact further downstream in the middle and lower areas of the fan. Such a pattern of wadi recharge was observed in the limestone aquifer of the Wadi Rawnab area of central Oman where it was shown that on passing down wadi the groundwater became more isotopically depleted and fresher. An explanation was that only the larger storms, which were both fresher and the most isotopically depleted reached the lower parts of the wadi. Of the 5 bores in this group, 3 were shown by Cansult (1986) to have high tritium values corresponding with the levels in modern rainfall from the Capital Area, and suggesting recent recharge.

A notable departure from the line occurs in the case of the "Deep Fresh" bores which lie well to the right of the line and which are the most depleted in deuterium. In the cases of KWD- 1 and 3L, these are fossil groundwaters with radiocarbon dates of 3000-5000 years BP and 5000 to 10000 years BP, respectively (Cansult, 1986). Both bores lie upbasin of the seawater intrusion. The KWD-2 bore is brackish. It is screened across a large fresh brackish water interval and represents mixture of the deeper freshwater and the overlying transition water. By contrast, the RGS-2L bore is surprising in that it is a deep freshwater bore, yet does not have the isotopic character of the other deep fresh bores. This cannot be explained by mixing since it is screened across a narrow interval from 319 m to 325 m depth, in a fresh zone which occurs beneath the seawater intrusion. This is supported by its low salinity which shows that it is not influenced by the intermediate depth seawater, and strong upwards directed head gradients indicate no hydraulic connection with shallow fresh water The RGS-2L bore lies on a different flow path to the west of the KWD flowline, and may represent more recent groundwater to that occurring in the KWD bores and hence a more active flow path.

The bores BZ-3, JT-30 and JT-32 lie well to the left of both water lines. The BZ-3 water lies outside the range of most 'normal' groundwaters in northern Oman. They come from the western part of the Al Khawd Fan, in the interfluve areas between the active flow channels, and occur essentially along a flow path from the head of the fan towards the coast. Apart from general suggestions that the waters may be influenced by processes which cause and oxygen shift such as an oxygen exchange with hydrogen sulphide gas and other hydrocarbons, or as a result of the oxidation of silicates to clay, there is no ready explanation for these results. The data does indicate, however, that for the western part of the Al Khawd Fan there is a somewhat different flow pattern or behaviour to that in the east and central parts.

CONCLUSIONS

The $\delta^{18}O$ and δD relationship for rainfall from northern Oman is $\delta D = 5.1\ \delta^{18}O + 8$ with a correlation coefficient of $R^2 = 0.86$. This is very similar to that derived by Gibb (1976) for Bahrain, with the high altitude rainfall at Saiq showing an almost identical relationship to Gibb's Bahrain MWL.

A $\delta D/\delta^{18}O$ water line derived from the groundwater systems on and adjacent to the Jebel Akhdar gave a relationship $\delta D = 5.1\ \delta^{18}O + 3$ with $R^2 = 0.92$. While derived for groundwaters from the limestone catchments this relationship also holds for other groundwater types across northern Oman. It provides a basis for examining the relationship between groundwaters in the upper catchments and those on the Al Batinah coastal plain and the interior plains, for example the Al Khawd Fan.

The groundwater data shows a clear elevation effect, not observed in the rainfall. Across the Jebel Akhdar there is an increase in δD and $\delta^{18}O$ in the groundwater of the limestone aquifer system from west to east. The most depleted groundwater ($\delta D > 10$; $\delta^{18}O > 3$) is restricted to the eastern parts of the Jebel Akhdar and to the upper catchments of the northern flowing wadis. It is also present in some springs and aflaj emerging at the foot of the Jebel in Wadi Samail to the east. However, high altitude depleted groundwater is not observed in springs emerging along the southern flanks of the Jebel Akhdar.

A plume of isotopically depleted (higher altitude) groundwater ($\delta D > 10$; $\delta^{18}O > 3$) emerges from the eastern parts of the Jebel Akhdar and passes, through a gap in the ophiolitic 'barrier', northwards across the lower catchment of the Wadi Al Maawil towards the coast near Barka. Apart from its stable isotope content, the presence of this plume is reflected in relatively high Ca/Mg ratios of groundwaters compared to those occurring elsewhere along the coast, where the groundwater is derived from ophiolitic catchments. This is seen as an important pathway for groundwater passing from the limestone catchments of the Jebel Akhdar onto the coastal plain.

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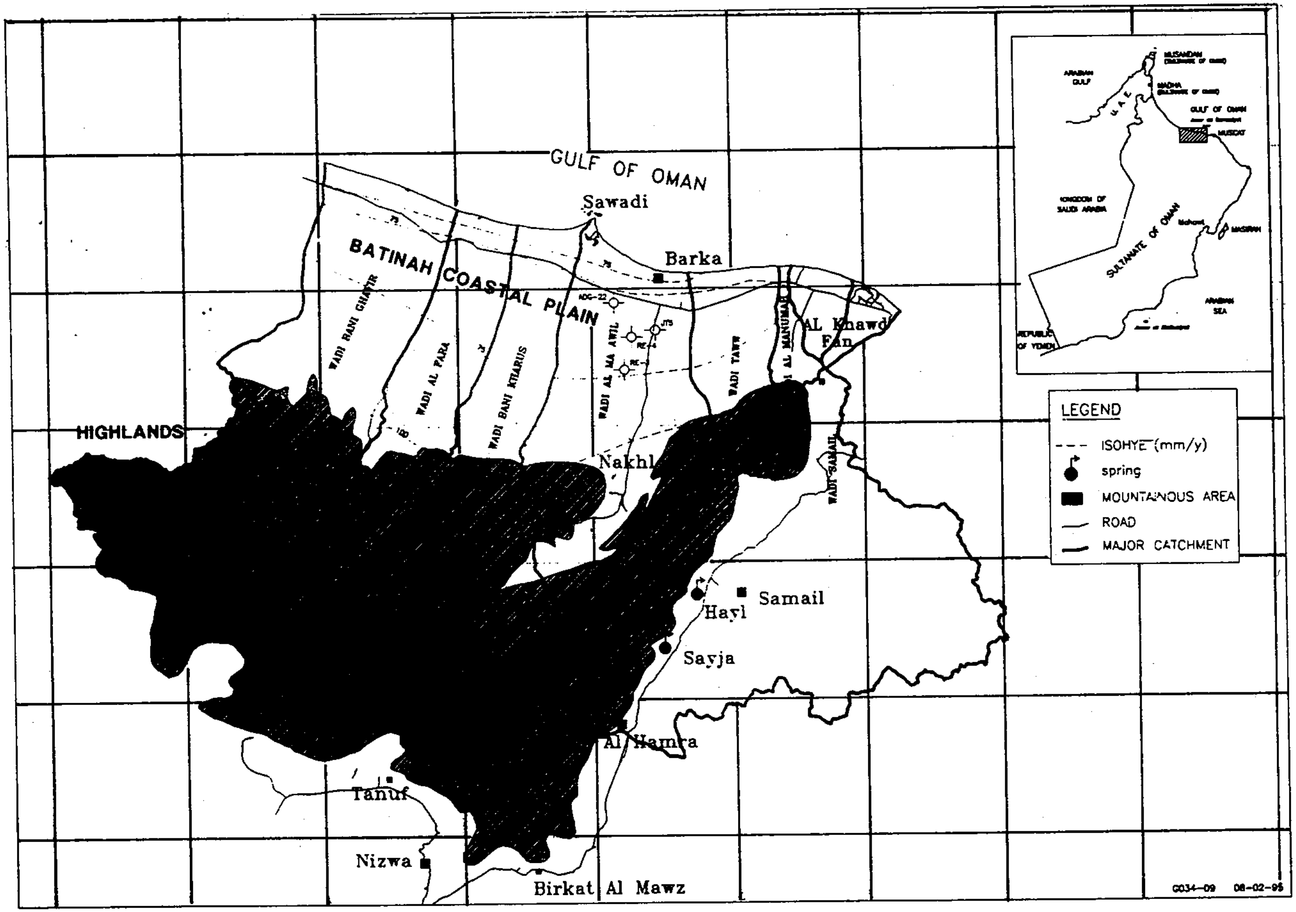


FIGURE 1. STUDY AREA

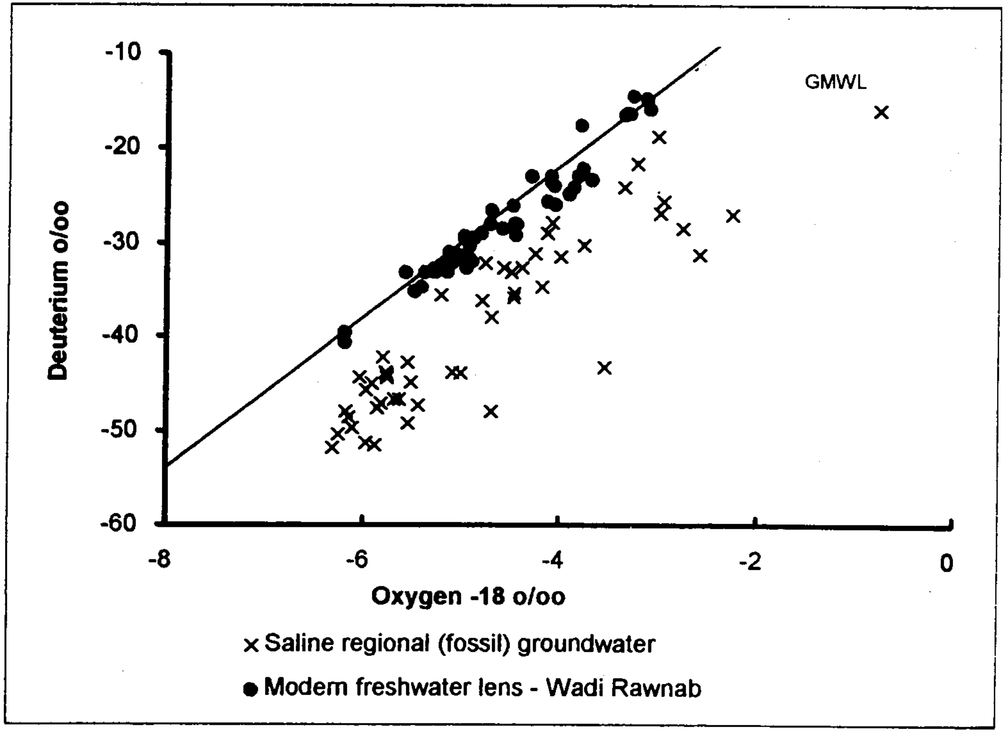


Fig. 2 Deuterium versus oxygen-18 for modern day and fossil groundwater in the Al Wusta Region of central Oman

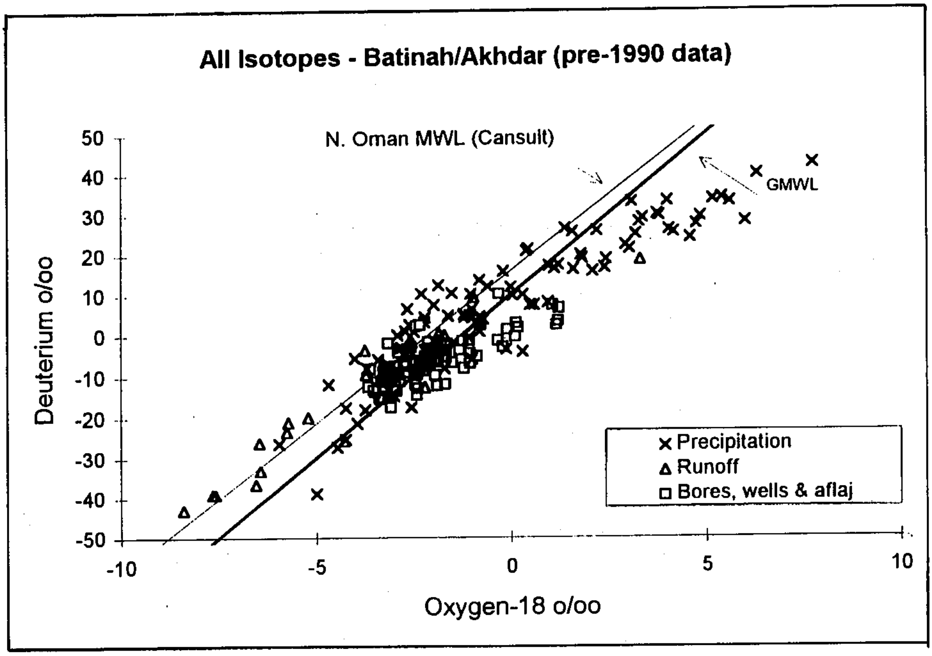
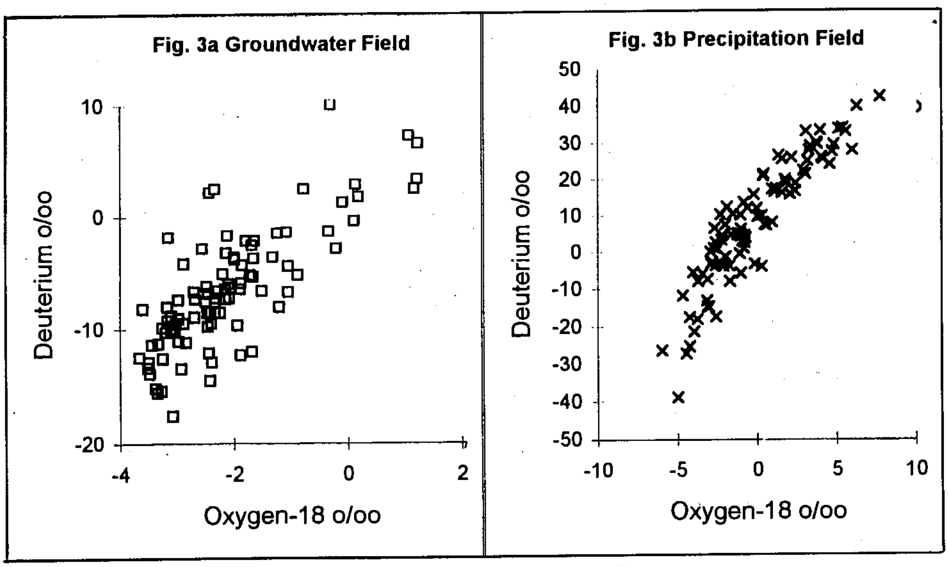


Fig. 3 δD v $\delta^{18}O$ for precipitation, runoff and groundwater (northern Oman - pre-1990 data set)



Figs 3a and 3b - Details of groundwater and precipitation fields

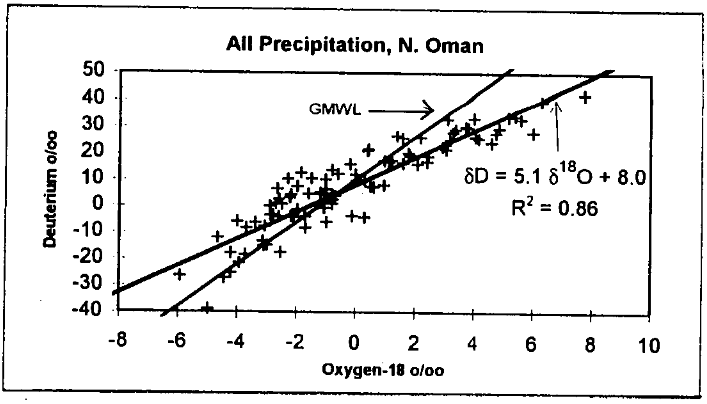


Fig. 4 Deuterium versus oxygen-18 for northern Oman precipitation

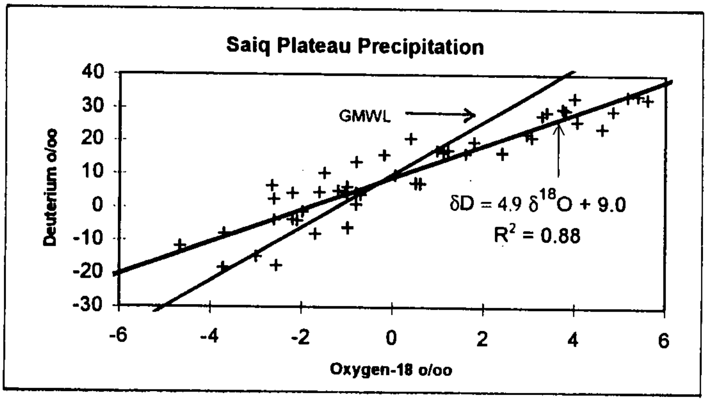


Fig.5 Deuterium versus oxygen-18 for the Saiq Plateau

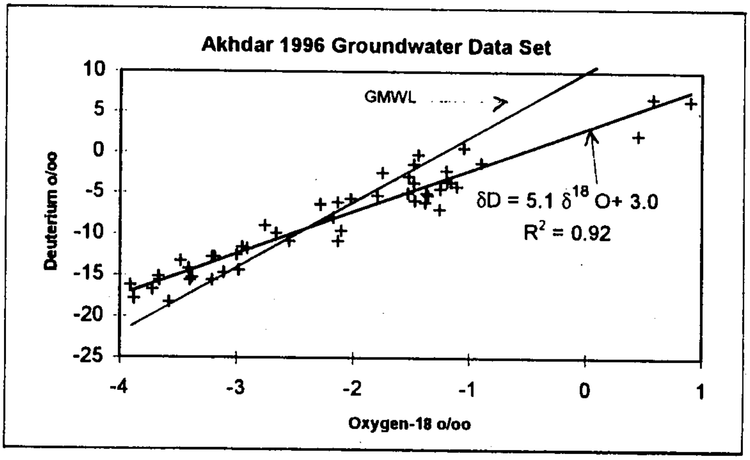


Fig.6 Deuterium versus Oxygen-18 for the Jebel Akhdar region 1996 dataset

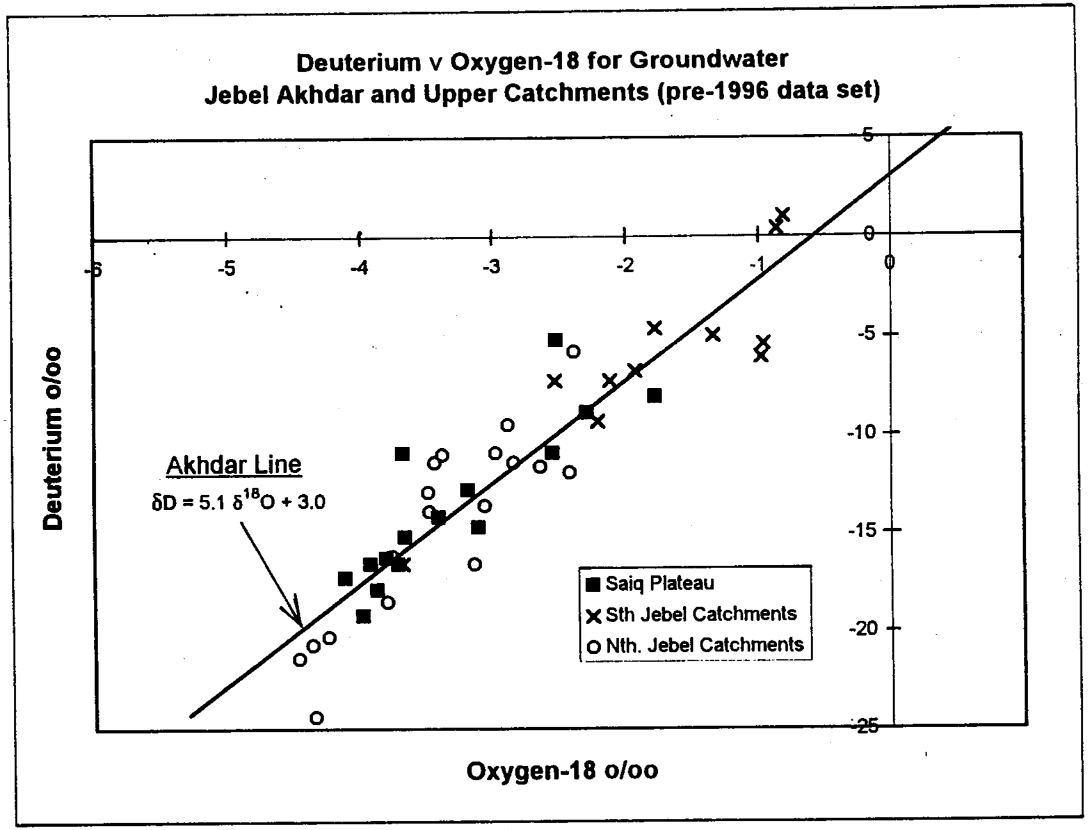


Fig. 7 δD vs $\delta^{18}O$ - Jebel Akhdar and upper catchments (pre-1996 data set)

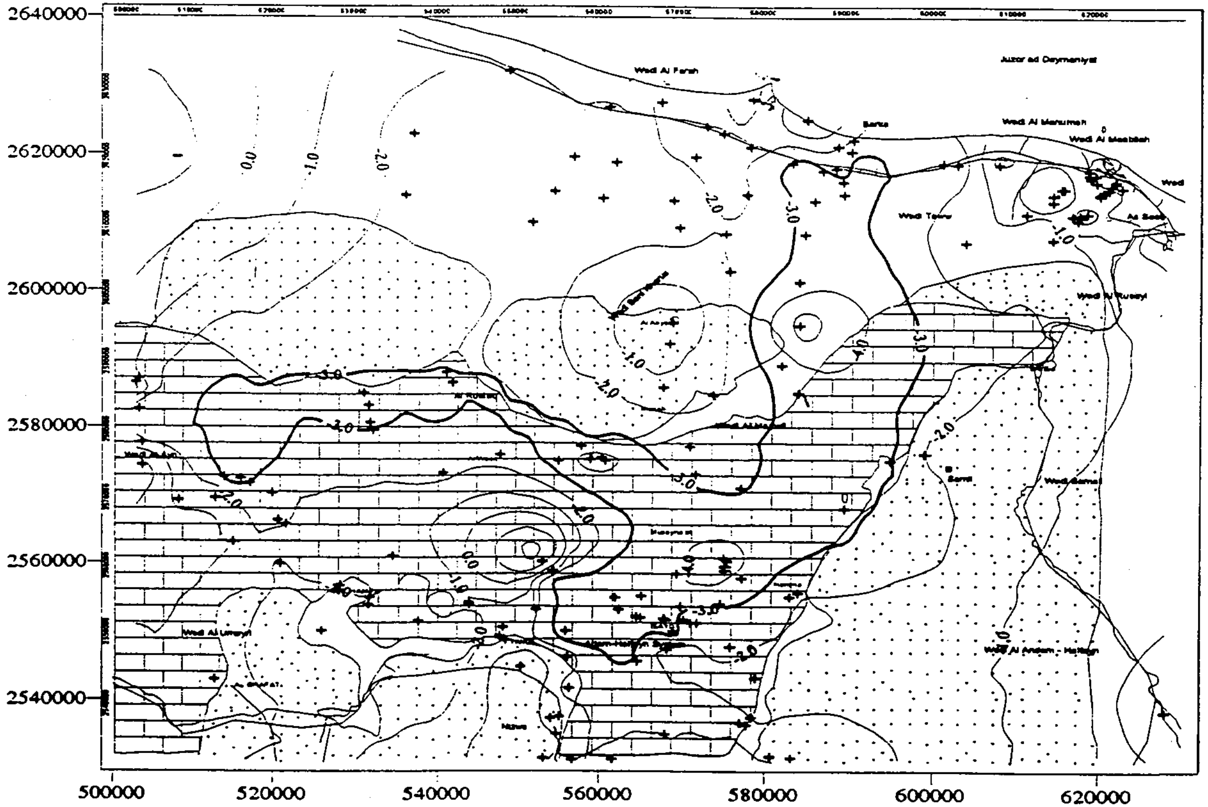


Fig.8 : Oxygen-18 Distribution in Jabal Akdhar Catchment and East Batinah Coastal Plain

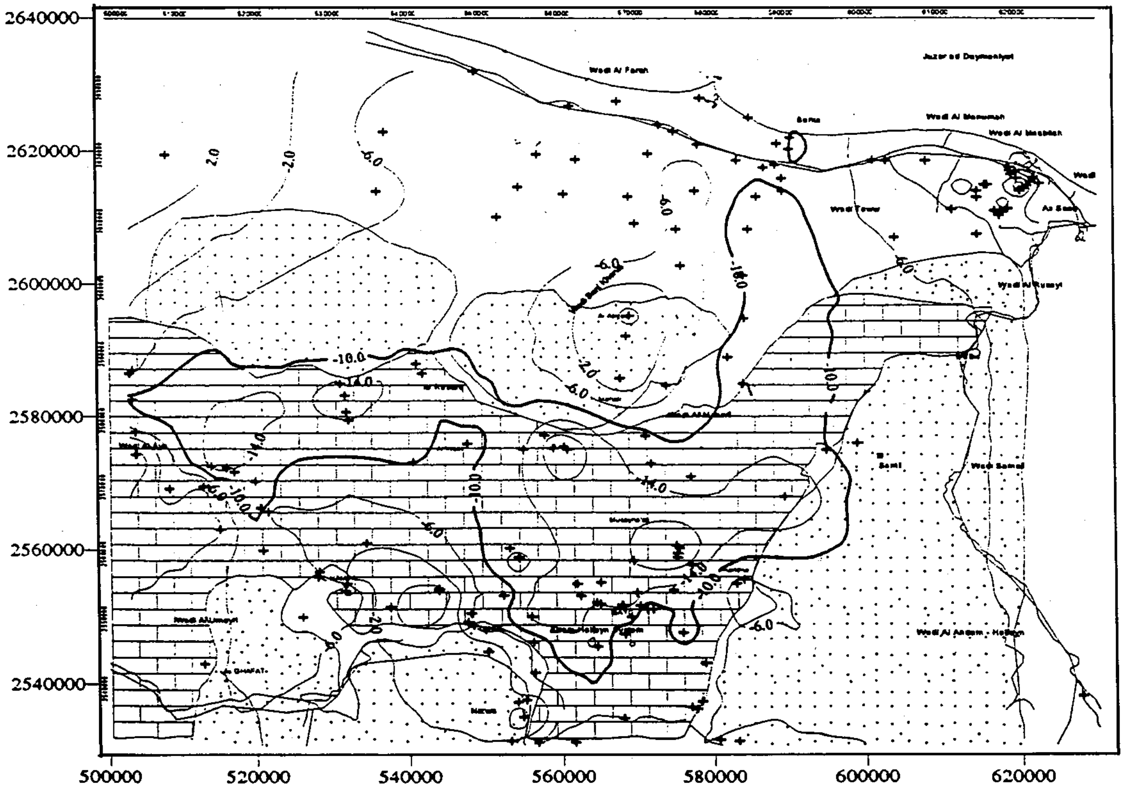


Fig.9 : Deuterium Distribution in Jabal Akdhar Catchment and East Batinah Coastal Plain

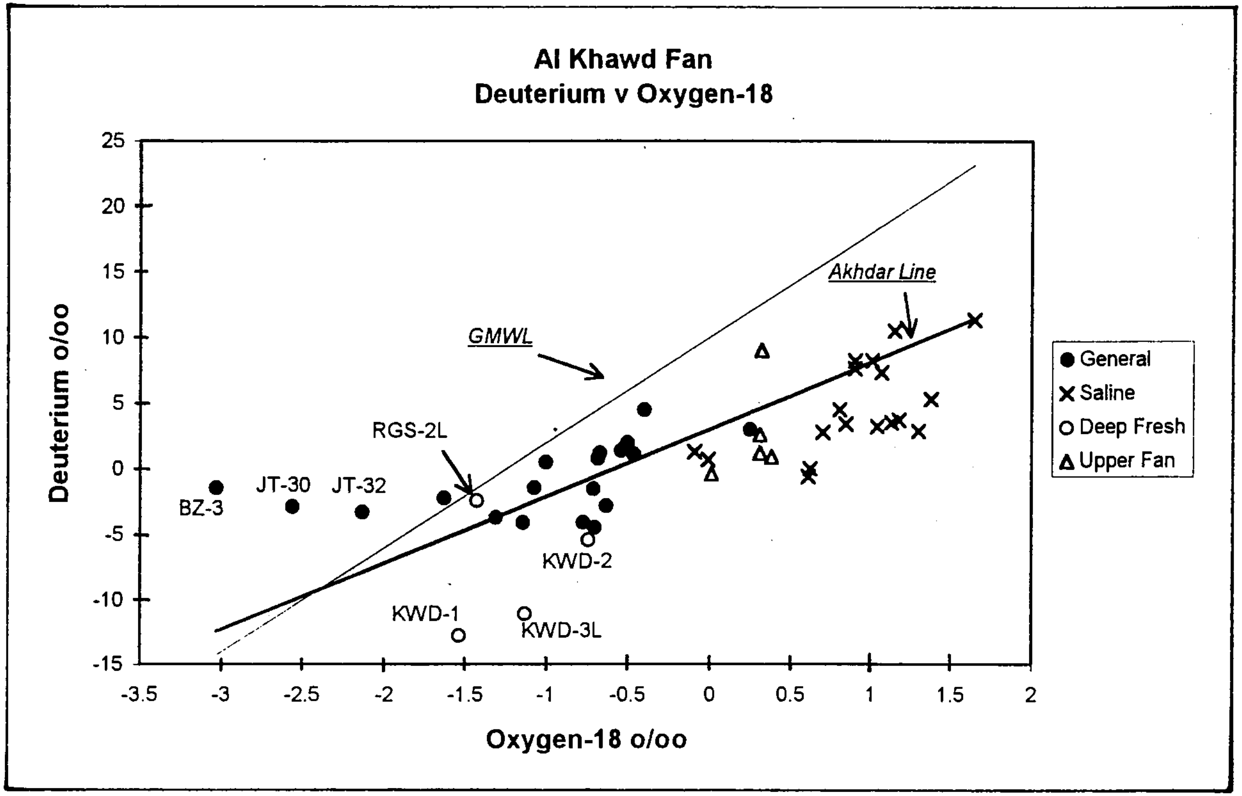


Fig. 10 δD vs $\delta^{18}O$ in the groundwater of the Al Khawd Fan

Use of Geophysics for Water Resources Assessment in Oman: A Review

M.E. Young, Nasser Al-Touqy, Said Al-Hinai and Ali Al-Ismaily

USE OF GEOPHYSICS FOR WATER RESOURCES ASSESSMENT IN OMAN: A REVIEW

M E Young, Nasser Al-Touqy, Said Al-Hinai and Ali Al-Ismaily
Ministry of Water Resources
Ruwi 112, Sultanate of Oman

ABSTRACT

Geophysical methods have been applied widely in Oman to the exploration and assessment of groundwater resources and to the assessment of potential sites for the construction of recharge dams. Aquifers in the Quaternary gravels of the Batinah and Salalah coastal plains have been mapped by a combination of time-domain (transient) electromagnetic (TDEM) sounding and deep seismic reflection. TDEM is also the preferred tool for rapidly and accurately mapping the depth and extent of saline intrusion. In the confined wadis in the foothills of the Northern Oman Mountains, alluvial or shallow bedrock aquifers are important; the geotechnical characteristics of sites in these wadis may also be assessed for artificial recharge. These are more difficult locations for geophysical surveys because of topographic restraints, bouldery ground conditions, and the physical inconsistency of the rocks. Ambiguity of geophysical interpretations arises from the variable physical properties of the Samail ophiolite, the marine Hawasina Group bedrock, and the variably cemented and argillaceous wadi sediments. These sites are best investigated with a combination of methods: shallow seismic profiling, TDEM sounding, resistivity and induced polarisation sounding or profiling, and gravity profiling. In the gravel piedmont important aquifers lie in paleochannels separated from the modern active wadi channels and these have been successfully mapped with resistivity and TDEM profiling. South and west of the Northern Oman Mountains, aquifers lie in the Tertiary Upper Fars Formation and overlying alluvium. Variations in formation resistivities, measured by TDEM, indicate variations in groundwater quality, and this method has been a principal tool for siting exploration boreholes. The base of the aquifer is often clearly characterised by a sharp resistivity contrast with the underlying argillaceous formation of the Middle Fars.

Keywords: Geophysical exploration, alluvial aquifers, Oman, saline intrusion, recharge dams.

GEOPHYSICAL RESPONSES OF HYDROGEOLOGICAL MODELS

Coastal aquifers

Electrical and electromagnetic (EM) methods have been used to mapping the lithology and salinity of the alluvial coastal aquifers, which support a high proportion of the population. On the Batinah Plain (Figure 1), Tertiary to Recent alluvium overlies Paleogene marine sediments and rocks of the Cretaceous Samail nappe. In simple terms the alluvial aquifer comprises three principal zones: an upper zone of permeable alluvium with water quality of 300-1000 mg/l NaCl is the main aquifer zone; this is underlain by clayey gravels with interbedded calcrete and claystone bands, and at depth by cemented gravels or limestone.

The electrical resistivities of these three units differ significantly. Relative to the upper alluvium, the resistivity of the clayey gravels is reduced by the clay content; the resistivity of the deepest layer, the cemented gravels, is increased by the reduction in porosity. These contrasts are exploited by electrical and electromagnetic sounding methods to map the boundaries of these zones and the variation of resistivity within the zones. Figure 2 shows a south-north resistivity cross section across the Batinah in the vicinity of Barka: the three zones are readily distinguished by their different resistivities. The resistivity of the upper gravels decreases slowly towards the north, due to the increasing fines content, and decreases sharply at the coastal strip where salinity exceeds 4500 mg/ NaCl in areas affected by irrigation returns and saline intrusion. The base of the main aquifer and the base of the less permeable clayey gravel aquifer zone are well defined and the thicknesses of the zones have been contoured from a network of intersecting profiles.

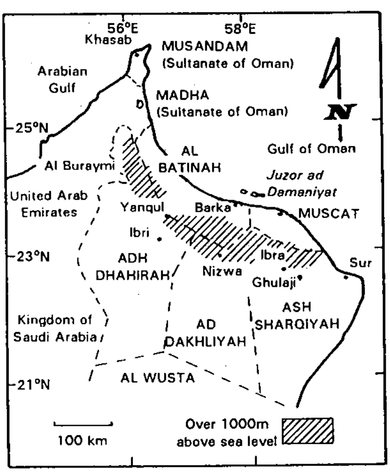


Figure 1 Sultanate of Oman, north of 21 °N

These soundings were acquired with a transient or time-domain electromagnetic (TDEM) survey sounding system which is particularly well suited to mapping electrically conductive zones. The characteristics of the electromagnetic field are interpreted in terms of the thickness and resistivity of a simple layered sequence, a model which is particularly appropriate on the coastal plains. Figure 3 shows a typical sounding, adjacent to the borehole 21-3 (Figure 2), together with the set of simple resistivity-depth models interpreted from the data. The base of the upper gravels is particularly well resolved, the base of the clayey gravels less so. The method is focused and, for the same transmitter dimension, provides deeper penetration than the longer established method of electrical resistivity sounding using arrays of electrodes. It is rapid in use, particularly because electrical contact with the arid ground is not required. The use of TDEM elsewhere in the Gulf region has been well described by Fitterman [1].

On the Batinah Plain seismic reflection previously acquired by oil companies has been useful in mapping the limits of the alluvium and the zones of cementation in the clayey and cemented gravel zones.

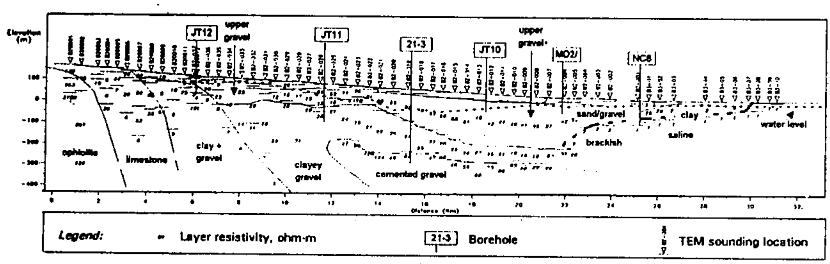


Figure 2 Batinah Plain: TDEM resistivity-depth cross section

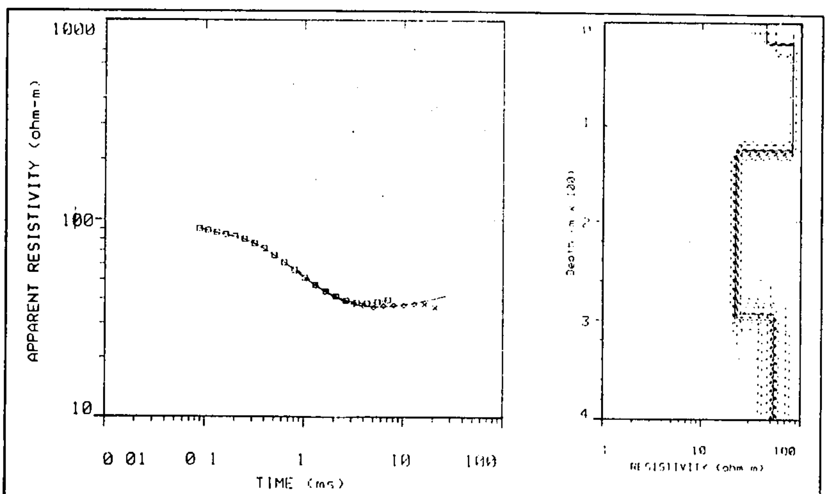


Figure 3 Batinah Plain: TDEM sounding and suite of interpreted resistivity-depth models

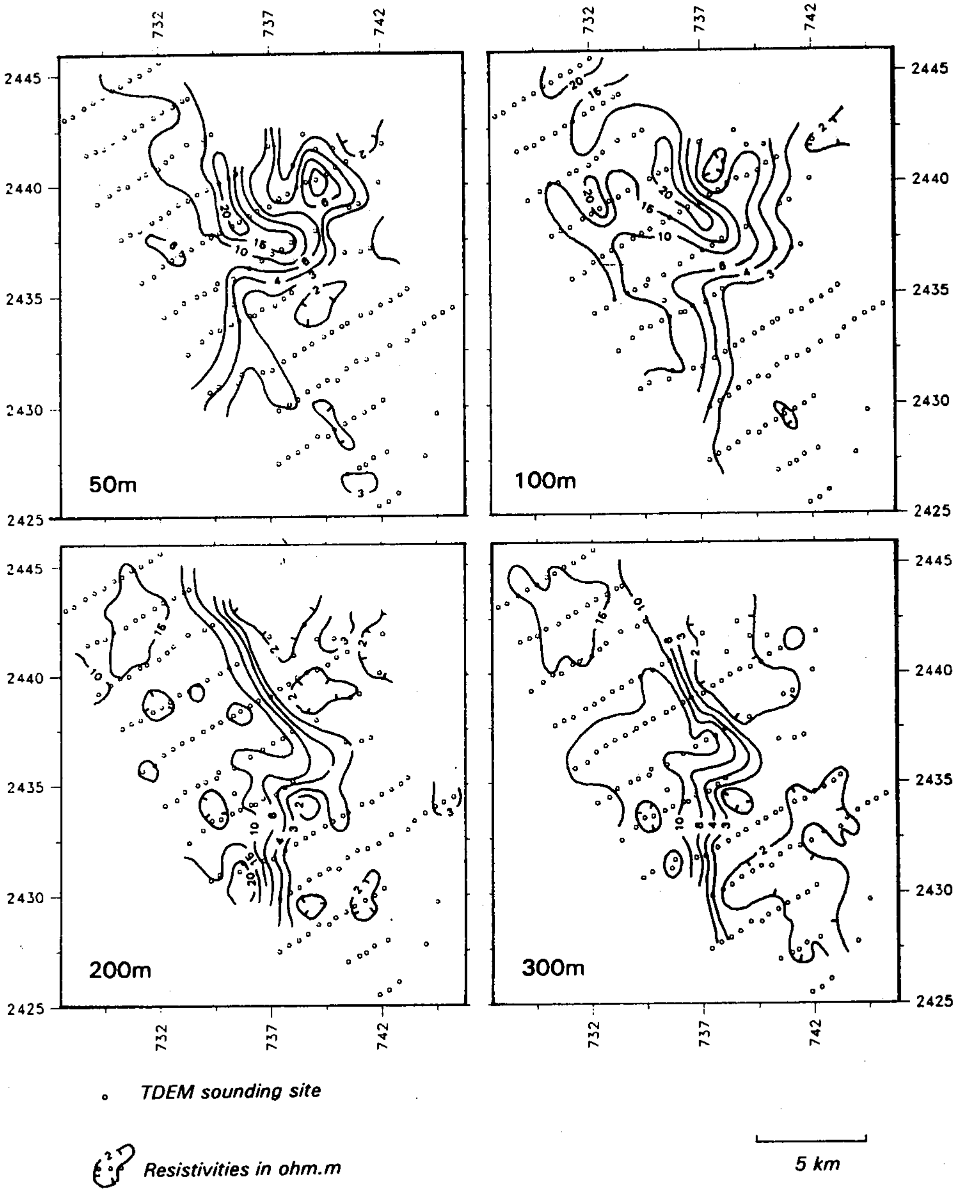


Figure 5 Sharqiyah: resistivity contours at four depths below ground level in a saline zone

Coastal saline intrusion

Saline intrusion is a serious source of pollution of coastal areas of Oman. The depth and inland extent of the intrusion can be accurately mapped with TDEM sounding, by virtue of its commensurate with these rock types. The interpreted model concurs well with boreholes sûbsequently drilled adjacent to soundings PV01-2/3 (Figure 7).

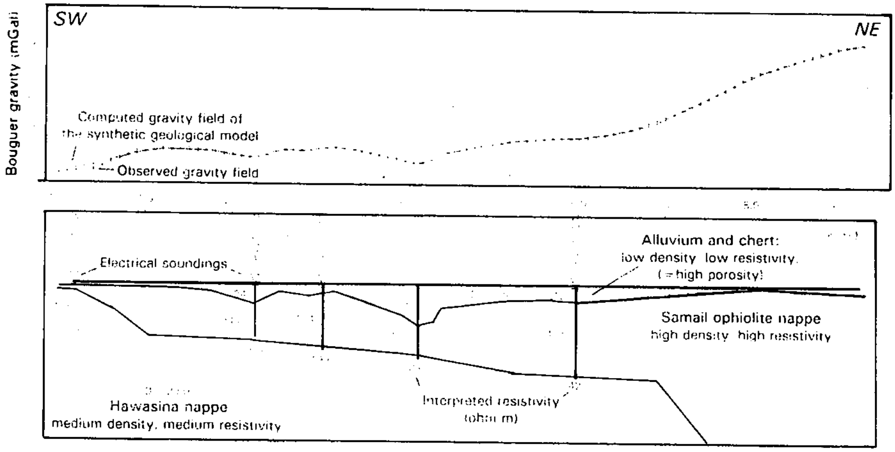


Figure 6 Sharqiyah: gravity profile across Wadi Al Batha,

In another area of Sharqiyah, also over ophiolite bedrock, resistivity and gravity were used to investigate a proposed recharge dam site. The contours (Figure 8) show low electrical resistivity (high conductance) and low gravity downstream of the proposed site, both indicative of the high porosity desirable in the spreading area. However, seismic survey across the site showed relatively high velocity, indicative of cemented alluvium, and this was confirmed by drilling in this case. The high porosity and low resistivity arise largely from the clay component of partly cemented, but less permeable, alluvium overlying the main aquifer zone. Recharge potential is limited to a shallow 5 m thick band of dry surface alluvium which was clearly characterised by low velocity and high resistivity.

In a similar situation in the foothills of the mountains at the northern end of the Batinah Coast, combined gravity, resistivity and induced polarisation was used to resolve the potential ambiguity of geological interpretation. Induced polarization (IP) measurements may be made simultaneously with resistivity. IP chargeability is a measure of the capacity of the earth to polarise during the passage of electric current and varies over different rocks in a manner different from resistivity. In the hydrogeological context, IP variations generally reflect the distribution of clay minerals or varying degrees of serpentinisation. Figure 9 shows a cross plot of resistivity and IP values of layers interpreted from 43 electrical soundings at the Northern Batinah site, showing the characteristic clustering of signatures of the principal rock types.

The areal outline of ophiolite bedrock, facies variation within bedrock and structures such as faults and fractures are best determined by magnetic survey. The contrast of the magnetic properties of the ophiolite compared with alluvium or other sedimentary rocks is very well defined. Airborne magnetic surveys have been conducted in Oman in recent years by the Ministry of Petroleum and Minerals and by the Ministry of Water Resources and clearly delineate the ophiolite thrust front and structures within the ophiolite, which are significant hydrogeologically. The high resolution of recent surveys has also revealed subtle magnetic signatures in the alluvium which may indicate accumulation of heavy minerals in paleochannels of possible hydrogeological significance. Airborne electromagnetic surveys for geological mapping and to map variations in water quality have not yet been made in the Sultanate.

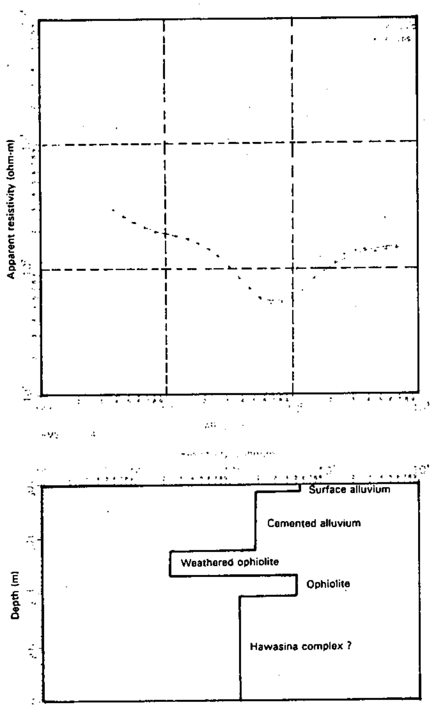


Figure 7 Sharqiyah: resistivity sounding and interpreted model of sounding PV01-03

Interior wadis - Hawasina bedrock

TDEM sounding is the preferred method for bedrock mapping where the bedrock is Hawasina Complex, as the method is particularly sensitive to low resistivity formations. Figure 10 shows a cross-sounding and interpreted model of section from a wadi near Yanqul, assessed for a possible recharge damsite. The bedrock profile is clearly mapped and subsequent drilling intersected bedrock within 2 m of the depth predicted. Lower resistivities in the overlying alluvium corresponded with a clay-enriched cemented zone. Although not an objective of the work, the borehole yielded 80 l/s from the aquifer zone in the bedrock channel detected, and was converted into a local supply.

Interior plains

Important aquifers lie in the alluvium and Tertiary Fars Group sediments in the plains to the south and west of the Oman Mountains, and in Ramlat Al Wahibah. TDEM sounding has been widely applied to mapping the low resistivity base of these aquifers and to mapping the water quality in the aquifer zones. Groundwater flow may follow paleochannels which can be mapped by surface geophysics if an appropriate physical property contrast exists.

Gulf region was first described by Woodward [4]. Clear and coherent seismic events have been mapped which correlate with cemented alluvium at about the present water level and at a possible earlier, deeper, water level. The configuration of the older Tertiary basin has been delineated and these data will provide useful estimates of the confines of the aquifer for groundwater modelling.

In Al Wusta, the arid central region of the Sultanate, where groundwater is generally very saline, TDEM has been used to map high resistivity anomalies associated with freshwater lenses. These lie at depths of 100-200 m in Tertiary carbonates beneath shallow surface depressions or beneath major wadis subject to occasional recharge by rare monsoon rains. These rocks are otherwise characterised by low resistivities and the resistivity anomalies appear to be related to the leaching of saline water from the rocks overlying the lenses, by the recharge process.

CONCLUSIONS

Surface geophysical surveys have been applied widely in the Sultanate to map lithology, particularly bedrock, to map salinity, and for engineering purposes. These applications have been most successful and quantitatively accurate where adequate contrasts in physical properties exist between the rock types and formations under investigation. Pronounced contrasts include those of electrical resistivity at the boundaries of coastal and inland saline zones, magnetic susceptibility between ophiolite and sedimentary rocks, and seismic velocity between saturated and unsaturated alluvium.

Transient electromagnetic sounding is the main method applied, to lithological mapping as well as to salinity studies. The Hawasina Complex bedrock or Tertiary Fars Group of many project areas is ideal for this application. Over ophiolite bedrock some combination of resistivity, induced polarization, gravity and seismic refraction methods is preferred, according to the local conditions.

ACKNOWLEDGEMENT

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Electromagnetic Detection of Underground Water

Mostafa S. Afifi

ELECTROMAGNETIC DETECTION OF UNDERGROUND WATER

Mostafa S. Afifi
Electrical Engineering Department
College of Engineering
King Saud University

ABSTRACT

Investigations are being made for use of electromagnetic radiation for detection of underground water. Frequencies in the Mhz and the Ghz range are analized in concern of ground absorption, water and soil reflectivity, as well as few other effects of minerals. The Mhz range is used successfully, with reported practical evidences in the literature. Interference patterns are used, with frequency variations, and with surface distance measurements of the interferance signals. The use of the VHF and the Ghz (L-Band) ranges is analized with application of the "Synthetic Aperture Radar". This has the superiority of synthesization, enabling the detection with focusing capability, for detailed investigations. Simulation results are shown, with small model laboratory scaled verification.

INTRODUCTION

More attention need to be given to applications of Electromagnetic radiation for the detection of underground water. Electromagnetic instrumentations have many control parameters and measurement flexibilities, in addition to high sensitivity of detection, and a variety of recent processing techniques which further its favour for many applications. Moreover Electromagnetic imaging, when perfected for underground applications, can provide a very valuable control of these valuable resources, without the need for expensive procedures of multi-well diggings around huge arid lands in the Gulf countries and the middle east. Additional important advantage of using electromagnetics is the capability of imaging using ground vehicles, aeroplanes or orbiting satellites, enabling simultaneous short time large area surveillance.

The electromagnetic spectrum is wide, making it easy to select adequate frequencies for different applications. Electromagnetic signals are also available with high power transmitters, sensitive receivers, active & passive varieties of antennas, and modern high speed processors; especially in the medium frequency (MF), HF, VHF, and the low GHz range of the frequency spectrum. These low frequencies are favoured for underground investigations, in order to avoid the excessive high losses of the electromagnetic signals, at deep underground layers, of the higher frequencies [2]. In this paper a short review is first given for the use of MF [3,4 & 5], with citation of successes made early in this century, using this medium frequency range for detection of deep underground water resources. Attention to these efforts was given in a previous paper [1], published in "the Second Gulf Water Conference", and other details are given in the following section.

SINAI DESERT UNDERGROUND WATER DISCOVERIES

In the fifties, and early eighties, radio waves were used to search for deep underground water in Egypt and its Sinai desert. These successful investigations are reported in [3], [4], and [5]. Measurements of interaction between a direct surface wave, and another deep water reflected wave, were made. Both waves are radiated and received by two identical antennas, located on the surface sand, at a variable distance from each other. This was called variable distance interference fringes (VDIF). Or by using multiplicity of closely separated frequencies of the spectrum, with fixed distance between the antennas, which is called variable frequency interference fringes (VFIF). The frequency range of operation was the 300 - 4000 KHz. The analysis for the interference fringes and evaluation of the electromagnetic propagation inside the earth and at its surface was made in [4], and in [5]. The configuration of the setup and the simple relevant equations are shown in Fig. 1. In this figure the frequency variations are between 800 KHz and 1100 KHz, in steps of 1 KHz. The difference in frequency between the peak levels of the received signals (as shown) are approximately 102 KHz for a major water reflection at a depth of 800 meters. Such an ideal case assumed homogeneous underground media between the earth surface and the deep underground water level. In reality this assumed homogeneity can rarely exist, and different ground layers, generate wave dispersion causing distortion of the neatly drawn fringes of Fig. 1. Such a practical situation is analyzed and explained in reference [3]. Inspite of such dispersion the distance between the fringes were accurate enough to indicate the water depth, as demonstrated practically in the cities of "Nikhil", "Khabra", and "Abu-Aweigla", of the Sinai dessert. For the borings at "Nikhil" water was found at 875 meters below the ground level (with EM measurement prediction of 885 meters), and for the borings at "Khabra" water was found at 790 meters below the surface (with EM measurement prediction of 835 meters).

The technology described in figure 1 is rather old and new developments of signal processing are now used to interpret underground reflections. These are classified under the subject of "ground penetrating radar" (GPR). This technology has the same basics, as previously explained in figure 1, using a surface transmitting and receiving antennas, with the possibility of simultaneously moving both of these antennas, or by using only one moving antenna for transmission and reception of radar waves. These can be continuous waves (CW), or pulsating waves. These are called "CW radars", or "Pulsating radars". These radars can also move at specific distances above the surface of the earth, using vehicles, aeroplanes or orbiting spacecrafts. Ground Penetrating Radars can discriminate between objects under ground using only one frequency, or it can use different frequencies to increase the accuracy of determination of the underground objects. The analysis in this paper handle the synthetic action of these systems, with some innovation in the signal processing technology, as explained in the following sections.

PRINCIPLES OF GROUND RADAR ANALYSIS

The processing of Radar returns using the Synthetic Aperture techniques is an accurate approach to remote underground sensing. It provides many advantages over conventional radars [9 & 10], resonant detectors [11], or sonic sensors. Its capability for high resolution, with focusing, and investigating processing flexibility [2 & 12], makes it the subject of research

FIG. 1 - ELECTROMAGNETIC INTERFERENCE FRINGES

$d := 1200$ distance between antennas in meters

$h := 800$ assumed water level below the surface of sandy soil

$f1 := 800000$ inetial frequency of operation $df := 1000$ frequency interval

$n := 1..300$ number of frequencies used $f_n := f1 + n \cdot df$

$\alpha s := 0.0001$ $\alpha u := 0.002$ are the attenuation coefficients of the surface and inner waves

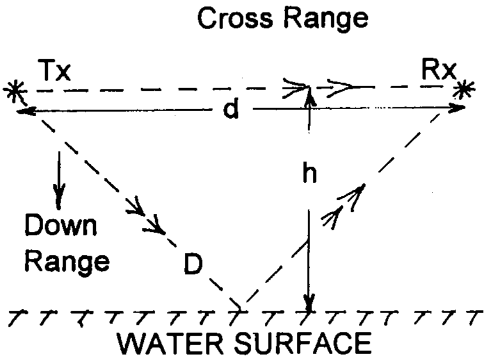
$\beta s_n := \frac{2 \cdot \pi}{3 \cdot 10^8} \cdot 1.75 \cdot f_n$ $\beta u_n := \frac{2 \cdot \pi}{3 \cdot 10^8} \cdot 2.5 \cdot f_n$ surface & inner phase coefficients

$i := \sqrt{-1}$

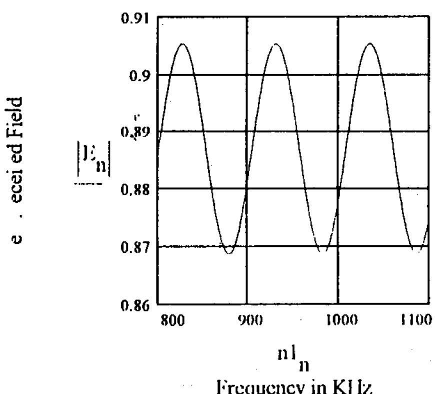
$D := \sqrt{(2 \cdot h)^2 + (d)^2}$ is the travel distance underground

$E_n := e^{-\alpha s \cdot d} \cdot e^{-i \cdot \beta s_n \cdot d} + e^{-\alpha u \cdot D} \cdot e^{-i \cdot \beta u_n \cdot D}$ is the simulated received field

$n1_n := n + 800$ The frequency of operation in KHz



THE MEASUREMENT CONFIGURATION



EXPECTED IDEAL FRINGES

for applications with possible deep penetrability. It can then produce helpful detailed images, which can be applied to detect underground details of specific objects or mineral compositions. The weak underground penetrability of electromagnetic waves is a major prohibition for wide spread applications of ground penetrating radars (GPR), especially at high frequencies, where fine resolutions can be achieved. For example clay losses can be 300 dB per meter, at X-band frequencies but only a few decibels at VHF/UHF frequencies [2]. This difficulty is partially compensated for by the processing capability of the Synthetic Aperture Radar (SAR). SAR has the flexibility of motion, as it is carried on aircrafts or ground moving vehicles, permitting rapid production of two dimensional images, which can be later detailed investigated by many flexible processing techniques. The image plane is defined by the velocity vector, of the vehicle, and the antenna beam axis, which are mainly orthogonal to each other. These form the "cross range" and the "range" dimensions of the image, in similarity with the configuration of figure 1. Most of the under ground objects are imbedded in soil moisture and many obstacles exist, which makes it difficult to isolate the required object from its surroundings. Many problems arise for distinction of targets from its surroundings. For this purpose radar focusing is applied, by processing, to achieve better identification capability, using the cross range and the down range resolutions. The focusing capability is important in determination of the extent of regions of concern under ground. This processing capability is explained in the following section, and improvements of the resolution capability by employment of processing at different frequencies, in limited frequency ranges, and using new averaging and multiplication techniques, are demonstrated in further sections.

SYNTHETIC RESOLUTION OF OBJECTS

Computation of the resolution available from processing of the fields, picked up by measuring phasors along the synthetic length of the SAR, can be simplified by considering the phasing progressive addition of these phasors, during the processing procedure. It is simply that as large number of phasors are arrayed along the synthetic length, the resolution is determined from the beam width of the coherent contribution of the array. Such resolution is conditioned by the location at the focusing distance "R", where the difference in the path length contribution from the array edges is half of the wavelength. The sketch of Fig. 2 illustrates such a requirement, and the resolution "x" is attainable from the solution of the equation:

$$Lu - Li = \lambda/2 = [((Ls/2)+x)^2 + D^2]^{1/2} + [((Ls/2) - x)^2 + D^2]^{1/2}$$

yielding $rs = 0.5\,[\,(Dls)^2 + 0.25]^{1/2}$, where “rs” is the resolution related to the wavelength, and “Dls” is the distance to the target “D” related to the synthetic length “Ls”. This relation is plotted in Fig. 2. It can be seen that the minimum resolution (which is new information in this field) is a quarter of the used wavelength, when the synthetic length is larger than the distance to the target. It can be seen also that when the synthetic length is small relative to the distance to the target the resolution reduces to the well known relation [8 & 18]

$$x = \lambda D / 2Ls.$$

These analysis indicate that the resolution can be improved by control of the synthetic length, related to the distance to the target, and what is more important, the wavelength of radiation. As improvements of resolution are always desirable, the synthetic length gets the tendency to be increased. Hence work in the near field is a necessary consideration, imposing more requirements for the processing of signals. Note here also that the use of long synthetic length give higher potential for the possibility of attainment of good resolution along the range. Such a result is very useful in the applications enabling the production of three dimensional images for underground objects. This has the attention of many recent investigations [7, 9, 10, 13, 15, 16, 17, 19 & 20]. Our contribution in this concern is consized in the following.

When using the exact formulations explained in Fig. 2, the resolution across the range, and along the range, can reach the limit of a quarter wavelength, as previously explained. This agrees with the shown simulation curves of Fig. 3. Note that the simulations of this figure are exact, and can be implemented using modern computer technology applications, as also demonstrated in reference [7]. The attainment of good resolution along the range has special importance for applications of ground water suvailence. It enables the determination of the limits of water pockets in underground reservoirs. Such near field focusing effects are explained and demonstrated by simulation in reference [7]. More detailed examinations of the phenomenon are illustrated in the following section; especially when interaction effects of other possible obstacles in the vicinity of the focused interface between water and its surrounding objects can be filtered out.

FILTRATION OF INTERFERENCE EFFECTS

Multiple interference arises from multiple reflections, enhanced by the proximity of multiple object details, the direct leakage between the transmitter and the receiver circuits, and or other interactions causing noisy receiver field levels. Such effects can cause rapid image variations, which might be explained as possible details in the image. These are also enhanced by sharp resolution of the synthetic radar of the near range (when the synthetic length is needed to be larger than the range distance of the target). The solution to these problems is to process data at multiplicity of frequencies. Many processing schemes are being used [9, 12, 13 & 17]. These are involved, and need complex processing procedures. In this section we introduce simpler and more effective technology, which uses addition and multiplication of different responses of the used variety of frequencies. These produce more sharpness for the processed objects (for small signal to noise ratios) compared with the sharpness produced in the cited references. An example for this is demonstrated by using two point source elements, separated at a distance of 8.5 units, using a wavelength of three units, and simulated random interference fields (added to the values of $E_{m,}$ generated using the accurate formulation of Fig. 2). The simulated random interaction fields are equivalent to signal to noise ratio of 14 dB, whereas the used signal to noise ratio in the cited references was around 30 dB. The simulation frequencies are scaled up to 8, 10 and 12 GHz. The processed image (as formed of two distinct objects, at separation distance of 8.5 cm) is shown in Fig 4, where normal processing produces the two low level peaks. The addition processing produces the two higher, and sharper peaks. And the multiplication processing produces the two highest and sharpest peaks, with the recognizable exceptional resolution. Measurements without processing are also shown in the same figure.

This simulation is performed at the X-band frequency range in order to facilitate experiments using the available laboratory test setups. A field experiment would be done at the low VHF frequency range (at frequencies similar to those of Fig. 1) in order to verify the ability of the described advanced technology for improvements of the results of reference [5].

CONCLUSION

The described advanced analysis, using the synthetic aperture ground penetrating radar, is very promising for detection of underground water in arid lands. It is possible to use land vehicles, equipped with simple VHF, CW radio frequency equipments, with adequate Yagi antennas to demonstrate this capability.

FIG. 2. SYNTHETIC RESOLUTION AND FOCUSING

$n := 0..1000$

$Dls_n := 0.005\cdot(n+1)$

"Ls" is the used synthetic length & "D" is the distance of the detectable object

"rs" is the resolution of the radar detection of the target, derived from the relation

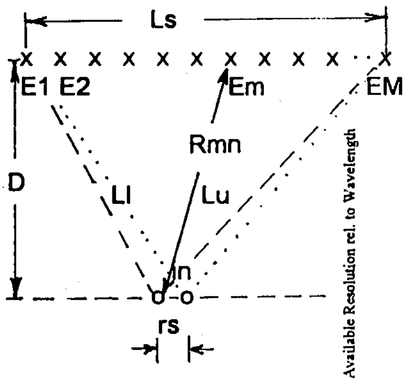
rs = (λ/2) [(D/Ls)^2 + (1/4)]^0.5 , Dls=D/Ls , rsl=rs/λ

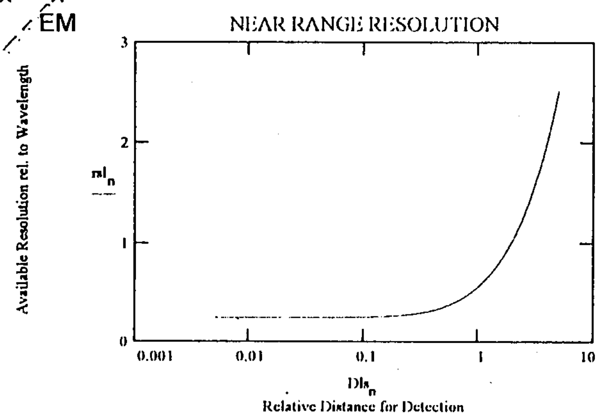
THE NEAR RANGE RESOLUTION LIMIT IS QUARTER OF THE WAVELENGTH

$$rsl_n := 0.5\cdot\sqrt{\left(Dls_n\right)^2 + 0.25}$$

$m := 0..150$ $D := 60$ $\lambda := 3.$

$x_m := -150 + m\cdot 2$





$$R_m := \sqrt{D^2 + \left(x_m\right)^2} \qquad i := \sqrt{-1}$$

$$\beta := 2\cdot\frac{\pi}{\lambda}$$

$$E_m := \frac{e^{-i\cdot 2\cdot\beta\cdot\left(R_m - D\right)}}{R_m}\cdot D$$

$mn := 0..40$

$xi_{mn} := -2 + mn\cdot 0.1$

$$Ri_{m,mn} := \sqrt{D^2 + \left(x_m - xi_{mn}\right)^2}$$

$nm := 0..60$

$Dj_{nm} := D - 1.875 + nm\cdot 0.0625$

$$Rj_{m,nm} := \sqrt{\left(Dj_{nm}\right)^2 + \left(x_m\right)^2}$$

$$im_{mn} := \sum_m E_m\cdot\frac{e^{i\cdot 2\cdot\beta\cdot\left(Ri_{m,mn} - D\right)}}{Ri_{m,mn}}\cdot D \qquad jm_{nm} := \sum_m E_m\cdot\frac{e^{i\cdot 2\cdot\beta\cdot\left(Rj_{m,nm} - D\right)}}{Rj_{m,nm}}\cdot D$$

FIG. 3. FOCUSING ACROSS AND ALONG THE RANGE

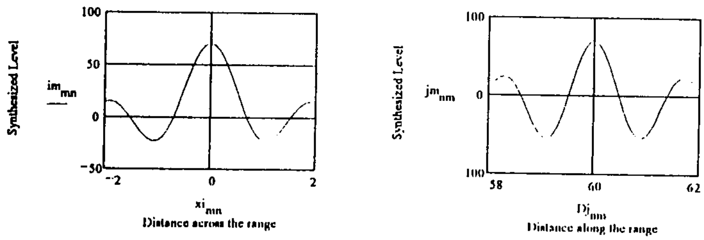
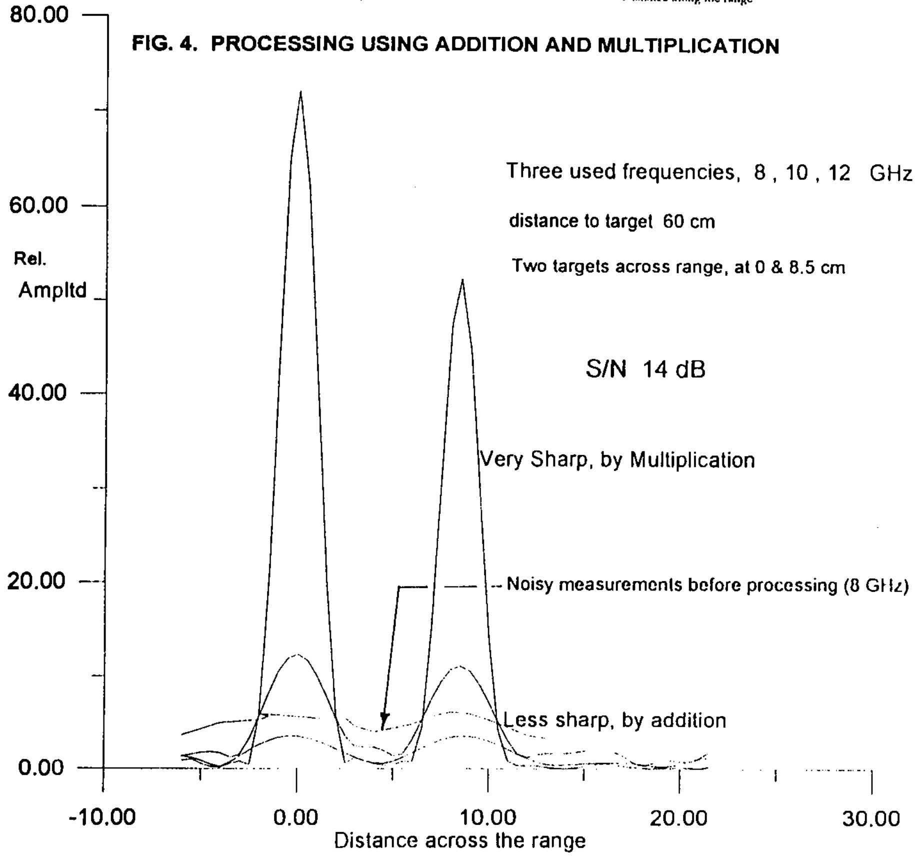


FIG. 4. PROCESSING USING ADDITION AND MULTIPLICATION



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Estimating Total Dissolved Solids Concentration of Groundwater Using Borehole Geophysical Logs

Daniel J. Bright and Mohamed Al Za'afarani

ESTIMATING TOTAL DISSOLVED SOLIDS CONCENTRATION OF GROUNDWATER USING BOREHOLE GEOPHYSICAL LOGS

Daniel J. Bright and Mohamed Al Za'afarani
National Drilling Company
P.O. Box 15287
Al Ain, United Arab Emirates

ABSTRACT

Numerous methods have been developed in the borehole-geophysical logging industry to estimate the total dissolved solids concentration of groundwater. Many of these methods are based on the reciprocal relation between the resistivity of groundwater and specific conductance. Three methods based on this relation - the ratio, cementation-exponent, and dual-water methods - were used to estimate groundwater dissolved solids concentrations in the alluvial and eolian sand aquifer throughout Abu Dhabi Emirate. The ratio and cementation-exponent methods are based on the formation factor concept of Archie; that is, water resistivities are determined only for permeable and essentially clay-free water-bearing zones. The dual-water method differs from the ratio and cementation-exponent methods because the effect of clay on the resistivity of water is accounted for by considering the conduction of bound water by ion exchange on clay particles; therefore, the volume of clay and bound-water conductivity must be known. Estimated dissolved solids concentrations using the ratio, cementation exponent, and dual-water methods were compared to the observed concentrations of dissolved solids in water from 43 wells. Estimated concentrations were calculated only for the contributing interval within the screened section of each well. Estimated TDS using the cementation-exponent and dual-water methods correlate slightly better to measured TDS (correlation coefficients equal to 0.97) than estimates using the ratio method (correlation coefficient equal to 0.93). The median error between estimated and measured TDS for the cementation-exponent and dual-water methods (about ±50 percent) was about half the median error using the ratio method (about ±100 percent).

INTRODUCTION

In 1988, the Ground-Water Research Project (GWRP), a cooperative program between the United States Geological Survey and the National Drilling Company of Abu Dhabi, began a reconnaissance study of the groundwater resources of the Emirate of Abu Dhabi. Shallow alluvial and eolian sand deposits form the principal fresh and brackish groundwater aquifer in the Emirate. Although varying in the degree of consolidation, clay content, and cementation, these deposits occur in most areas of the Emirate and, historically, have been the main source of water for municipal, agricultural, and industrial uses.

Borehole geophysical logging was a key component of the reconnaissance study. A comprehensive suite of borehole geophysical logs were collected at more than 40 sites to determine geologic and geohydrologic properties of the penetrated formations. The standard suite of logs included caliper, spontaneous potential, gamma-ray, microresistivity, dualinduction, and compensated neutron, density, and sonic.

The logging suite proved to be particularly useful in estimating total dissolved solids (TDS) concentrations of ground water. Three methods were applied in this study to estimate TDS of groundwater - the ratio, cementation-exponent, and dual-water methods. The parameters used to determine groundwater TDS in the ratio method are measured directly from the logs; as a result, the ratio method was routinely applied in the field to construct wells that are screened in zones that contain the best quality (lowest total dissolved solids concentration). In comparison, many of the parameters used to estimate TDS in the cementation exponent and dual-water methods were determined using computer programs and a more detailed analysis of the logs. As applied in this study, these methods generally were not applicable in the field, but used to determine more accurately the vertical changes in groundwater salinity. Vertical changes in salinity were determined for the purpose of estimating the volume of fresh and brackish groundwater storage in the alluvial aquifer.

This paper presents the results of the ratio, cementation exponent, and dual-water methods that were used to estimate the salinity of ground water in the Emirate of Abu Dhabi. The accuracy of each method is checked by comparing the estimated and measured TDS.

METHODS

The ratio, cementation-exponent, and dual-water methods are based on the formation-factor concept of Archie (1942) and the reciprocal relation between the resistivity of formation water and specific conductance. The formation factor concept is used to determined the resistivity of water from equations that relate the true resistivity of the formation to either the resistivity of the invaded zone (ratio method) or the porosity of the waterbearing formation (cementation-exponent and dual-water methods). Jorgensen (1989) concluded that, for many of the methods used to determine the resistivity of water, an accuracy of about ± 0.5 an order of magnitude is common for data collected from typical oil-field test holes with no prior knowledge of the quality of the logs. However, if logs are properly calibrated and parameters used to estimate the resistivity of water are measured accurately, errors between estimated and measured TDS often can be reduced to less than 100 percent (Jorgensen, 1991, 1996).

The ratio method is useful for determining TDS if there is some mud invasion of the drilling fluid. Consequently, for permeable zones where some mud invasion has occurred, the following equation was used to estimate the TDS concentration of formation water (Jorgensen, 1996, p. 520):

$$TDS = \frac{562{,}800}{(T_{mf}+7)\,(R_{mf})} * \frac{R_{xo}}{R_t} \qquad (1)$$

where:TDS is the total dissolved solids concentration, in milligrams per liter,

R_{xo} is the resistivity (mg/l) of the invaded zone, in ohm.meters,

R_t is the true formation resistivity, in ohm-meters,

R_{mf} is the resistivity of mud filtrate, in ohm meters, and

T_{mf} is the temperature of mud filtrate, in degrees Fahrenheit (F).

Values for R_{xo} for the invaded zone can be determined from a microresistivity log. The microresistivity tool usually produces measurements that represent a 3-inch or 4-inch depth of investigation. In most cases, invasion of mud filtrate more than 2 inches beyond the well bore can be expected, even in most clay formations (Jorgensen, 1996, p. 520). The true formation resistivity (R_t) can be measured using "deep looking" resistivity or induction logs. For this study, all R_t values were measured using an induction log.

The cementation-exponent method is based on the following equation (modified from Jorgensen and Petricola, 1994):

$$TDS = \frac{562{,}800}{R_t * \phi^m \, [(T_{ma} + (GTG)\,(depth)) + 7]} \qquad (2)$$

where: R_t is the true formation resistivity from the deep induction log, in ohm-meters,

ϕ is the effective porosity (decimal fraction, dimensionless),

m is the cementation exponent (decimal fraction, dimensionless),

T_{ma} is the mean annual air temperature, in degrees Fahrenheit,

GTG is the geothermal gradient, in degrees Fahrenheit per unit depth, and

depth is the distance below land surface, in feet.

The effective porosity was estimated by using the computer program LOGAN 2 (Log Analysis, version 2.0) developed by the GWRP (Jorgensen and Petricola, 1994). The program uses an iterative solution to determine a calibrated value of effective porosity the ratio of the volume of "free" water to the total volume. Free water is water that will drain by gravity from a porous medium and equals the difference between the total porosity (for example, from a neutron or density log) and the volume of "retained" water - water that does not drain easily from a saturated medium. Large quantities of water are retained by fine-grained material, such as clay. However, small quantities of water are retained by coarse-grained material, such as sand and gravel. The estimation of effective porosity is adjusted during numerous iterations of the program by comparing simulated values for the volume of clay and for the density of non-clay matrix material against measured or calculated values. A detailed discussion of the equations and algorithms used in the computer program are presented by Jorgensen and Petricola (1994).

The cementation exponent relates to the tortuosity of the flow path and the pore-throat dimension. This parameter i8 derived empirically and equals the negative reciprocal of the slope of the line defined by a log-log plot of porosity (in percent) and true resistivity of the water-rock system (Jorgensen, 1989, p. 16). Therefore, larger cementation-exponent values generally reflect increased content of high porosity, low resistivity formation clay. For the alluvial aquifer in the Emirate of Abu Dhabi, the cementation exponent varied between 1.20 - 1.6 (GWRP data files).

The estimated TDS using the dual-water method more closely approximates the formation-factor concept of Archie (1942): that the clay content of the sand formation being analyzed is relatively low. Equations based on this concept are not always suitable if the formation includes clay because the estimated conductivity is a function of both the conduction of "far" formation water and "bound" formation water. The conduction of far water (free water plus retained water) is by mobile ions; the conduction of bound water on the surface of clay minerals is by ion exchange. Bound water is water that is very tightly held by clay particles and is considered part of the matrix material.

In the dual-water method, the TDS of far water is estimated by iteration using the following equation (modified from Jorgensen and Petricola, 1994):

$$C_{fw} = \frac{(C_t/\phi_t^m)(V_{fw} + V_{bw}) - (C_{bw} * V_{bw})}{V_{fw}} \qquad (3)$$

where: C_{fw} is the conductivity of far water, in ohm^{-1}•meters^{-1},

C_t is the reciprocal of true formation resistivity (R_t) from the deep induction log, in ohm^{-1}•meters^{-1},

ϕ_t is the total porosity from the density and neutron porosity logs (decimal fraction, dimensionless),

m is the cementation exponent (decimal fraction, dimensionless),

C_t/ϕ_t^m is the reciprocal of formation water resistivity ($1/R_w$) and equals the conductivity of an equivalent water assuming clay-free conditions, in ohm^{-1}•meters^{-1},

V_{fw} is the volume of far water (decimal fraction, dimensionless),

C_{bw} is the conductivity of bound water, in ohm-1 meters-1, and

V_{bw} is the volume of bound water (decimal fraction, dimensionless).

The dual-water method algorithm is used by first determining the apparent water resistivity (R_w) using the same general equation as the cementation-exponent method, that is: $R_w = R_t * \phi_t^m$, where ϕ_t is total porosity and m is the cementation exponent equal to a constant value of 2.00. R_w is then corrected for the effect of clay by inserting the reciprocal of Rw into equation 3 (equal to C_t/ϕ_t^m) and estimating the conductivity of bound water (C_{bw}). An iterative procedure is necessary to solve for C_{bw} because it is a function of C_{fw}. For each borehole in the data set, the conductivity of bound water was estimated by Schlumberger Middle East using computer programs developed in cooperation with the GWRP. The remaining parameters in equation 3, volumes of free and bound water, were determined using a computer program developed by the GWRP (Jorgensen and Petricola, 1994, p. 32).

Estimates of ground-water TDS using the cementation-exponent, ratio, and dual-water methods were made only for the contributing intervals within the screened section of each well. Because downhole flowmeters were not part of the standard suite of logs, contributing intervals were defined, qualitatively and quantitatively, by permeability contrasts.

Dual-induction, compensated-sonic, gamma-ray, and caliper logs are good indicators of permeability. For example, if mud resistivity differs significantly from formation-water resistivity, a relatively large separation often occurs between the medium and deep induction curves within permeable zones. This information is checked on both the gamma and sonic logs for verification of permeable zones; permeable, clay-free zones have relatively low gamma-ray and travel-time values. Lastly, invasion of drilling mud into a permeable formation is reflected on the caliper log as a thick mudcake. Where permeability is low, the mudcake is often thin or absent.

For all zones that are qualitatively determined to be permeable, average values of intrinsic permeability were calculated using the following equation (Jorgensen and Petricola, 1994, p. 33):

$$k = (1 \text{ X } 10^4)(\phi_D^{4.5}) / S_{wi}^2 \tag{4}$$

where: k is intrinsic permeability, in millidarcies,

ϕ_D is porosity from the density porosity log (decimal), and

S_{wi} is the total irreducible water saturation.

Irreducible water saturation (S_{wi}) is equal to the volume of retained water divided by the volume of far water (free water plus retained water). Total irreducible water saturation is the sum of S_{wi} for a clay and S_{wi} for a non-clay porous material. Similar to the value of effective porosity used in the cementation-exponent equation, S_{wi} is estimated by iteration using a computer program developed by the GWRP (Jorgensen and Petricola, 1994, p. 33).

For the purposes of this report, a contributing interval is defined as a screened zone with an intrinsic permeability greater than 1,000 millidarcies (one md is equivalent to a hydraulic conductivity of 0.8 m/d). If calculated permeabilities for the contributing interval were less than 1,000 md, the entire screened interval below the water table was used in equation (4). The 1,000 md value represents an approximate lower permeability limit for low-yield aquifer material such as silty and clayey sand. Estimates of TDS for contributing intervals within the screened interval of the well were summed and a weighted-average TDS value calculated. Final estimated TDS is therefore weighted with respect to the thickness and permeability of the contributing interval; that is, TDS estimates for thick, permeable zones are given a higher weight than thin, less permeable zones. The same contributing intervals were used for the cementation-exponent, ratio, and dual-water methods.

Measured TDS concentrations were determined from complete chemical analyses of samples from 34 of the wells used in the data base. For the remaining 9 wells, "measured" TDS was calculated by multiplying the specific conductance by a factor determined using a least squares, linear regression method of correlation. The coefficient of determination (r2) for the regression analysis between specific conductance and measured TDS equaled 0.96.

RESULTS

Statistical analysis for a linear relation between estimated and measured TDS indicates good correlations for all three methods (Table 1). Estimated TDS using the cementation-exponent and dual-water methods correlate slightly better to measured TDS (correlation coefficients equal to 0.97) than estimates using the ratio method (correlation coefficient equal to 0.93). A correlation coefficient equal to zero indicates no correlation and a value equal to 1 indicates a perfect correlation.

Table 1. Comparison of estimated total dissolved solids concentrations from ratio, cementation-exponent, and dual-water methods to measured total dissolved solids concentrations

[TDS, total dissolved solids; mg/1, milligrams per liter; k, intrinsic permeability; md, millidarcies]

	Ratio Method	Cementation-Exponent Method	Dual-Water Method
All Samples - 43 wells			
Correlation coefficient (r)	0.93	0.97	0.97
Standard error (mg/1)	12,507	4,718	11,653 (5,310[1])
Median difference between estimated and measured TDS (mg/1)	-2,832	-566	-912
Median error (percent)	106	48	57
Salinity Zone			
Fresh (TDS < 1,500 ma/1, 13 wells)			
Median error (percent)	219	107	87
Brackish (TDS 1,500-15,000 ma/1, 23 wells)			
Median error (percent)	91	44	35
Saline (TDS > 15,000 ma/1, 7 wells)			
Median error (percent)	36	19	75
Permeability Zone			
Low (k < 1,500 md, 16 wells)			
Median error (percent)	157	58	56
Medium (k 1,500-10,000 md, 13 wells)			
Median error (percent)	95	51	57
High (k > 10,000 md, 14 wells)			
Median error (percent)	68	48	57

1 Equals the standard error for the dual-water method after elimination of one highly saline well (TDS equal to 127,000 mg/1).

Figure 1 illustrates the scatter of estimated TDS values for each method about a 1:1 ratio line - the line that would result if estimated and measured values were identical across the entire data range of measured values. Visual inspection of the plots indicate that the ratio method produces the largest scatter of data points. The scatter of data points for the cementation-exponent and dual-water methods are nearly equal and less than that produced by the ratio method. Moreover, the standard error of estimate for each method - a measure of the variation or scatter of estimated TDS about the line of regression (not shown in figure 1) - are lower for the dual-water and cementation-exponent methods (Table 1).

The median difference between estimated and measured TDS for all 43 wells indicates whether each method generally overestimates or underestimates measured TDS; that is, negative median values indicate overestimation and positive values indicate underestimation. The negative median difference values shown in Table 1 indicate that all three methods tend to overestimate measured TDS; the median difference is highest for the ratio method (-2,832 mg/l) and lowest for the cementation-exponent method (-566 mg/l). Overestimated TDS using the ratio and dual-water methods are clearly shown in figure 1 (values above the 1:1 ratio line). Overestimated TDS using the cementation-exponent method is less clearly shown in figure 1 because of less scatter (low standard error) and a more even distribution about the 1:1 ratio line.

For the entire data set of 43 wells, the cementation-exponent method produced results with the smallest median percent error between estimated and measured TDS (Table 1). In comparison, the median error for the ratio method (about 100 percent) is more than twice that of the cementation-exponent or dual-water methods (about 50 percent). The median percent error was determined by calculating the absolute value of the difference between measured and estimated TDS for each well, dividing by the measured TDS for each well, and then observing the median percent error for all 43 wells, times 100.

To illustrate the accuracy of each method over a range of measured TDS, the data set of 43 wells were divided into groups of fresh (less than 1,500 mg/l), brackish (1,500 to 15,000 mg/l), and saline-water categories (greater than 15,000 mg/l) (Table 1). Generally, the cementation-exponent and dual-water methods are accurate to within about 100 percent for fresh water and about 40 percent for brackish water. For both categories, the dualwater method produced the most accurate results, and the ratio method the least accurate - more than twice the median error of the other two methods. The larger median error for fresh-water samples may be due, in part, to the smaller denominator used for measured TDS (in comparison to brackish and saline zones) or to inaccuracies of the Archie assumptions in the fresh-water range. In fresh water with relatively high resistivity (Rw), the true resistivity of the saturated formation is no longer a

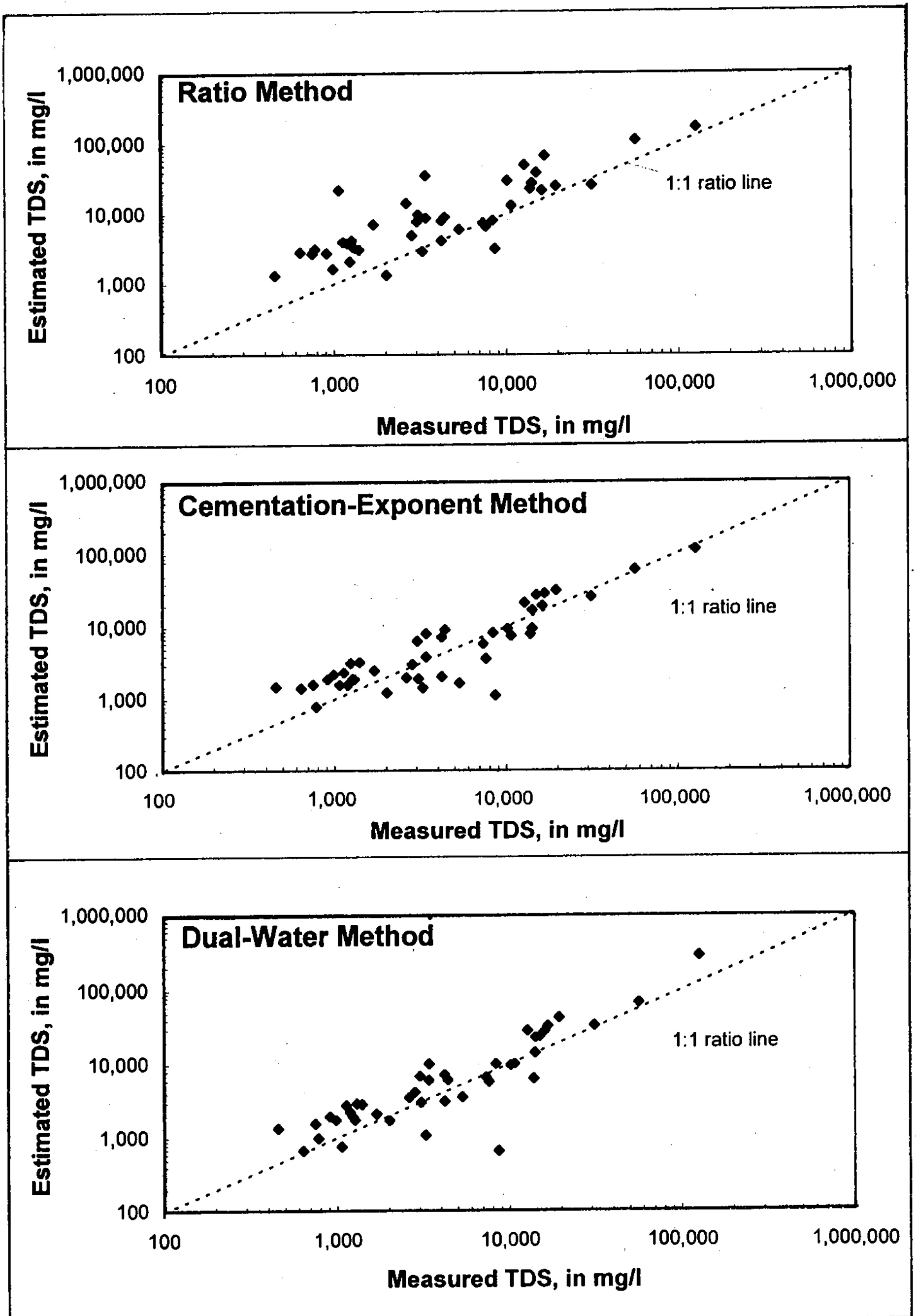

Figure 1. Relation of estimated and measured total dissolved solids using ratio, cementation-exponent, and dual-water methods.

function of pore-water conductivity, but may be influenced by surface conduction along the rock grains and ionic exchange between the grains and water (Jorgensen, 1990, p. 61).

The accuracy of the dual-water method significantly decreased in the saline-water range due to a large error in estimated TDS for one well containing water with high TDS (127,000 mg/l) - more than 5 times the measured TDS of any other well in the entire data set. The decreased accuracy of the method in the high-salinity range is probably due to the use of a constant cementation exponent in equation (3), rather than an empirically derived and variable exponent, such as that used in the cementation-exponent method (equation 2). That is, errors in the resistivity of water (R_w), due to small errors in the cementation exponent, give rise to large errors in estimated TDS in the high-salinity range because of the exponential relation between Rw and TDS.

The effect of permeability on estimated TDS was tested by dividing the data set into relative permeability zones of low (< 1,500 md), medium (2,500 to 10,000 md) and high (> 10,000 md) categories (Table 1). The cementation-exponent and dual-water methods again showed the best results (lower median error) about 50-60 percent median error for all permeability zones. Moreover, in comparison to the ratio method, the cementation-exponent and dual-water methods produced good results for the low permeability zone, of 58 and 56 percent median error between estimated and measured TDS, respectively. The low median error reflects the accuracy of using an effective porosity value for the cementation-exponent method. For the dual-water method, the low median error is principally due to correcting R_w for the conductivity of bound water in clayey sands. Median error values for the ratio method indicate that the accuracy generally improves with increasing permeability. In theory, the ratio method should produce better results with increasing permeability because at higher permeabilities a greater amount of mud invasion will occur - a basic requirement for using the ratio method (Jorgensen, 1996).

CONCLUSIONS

Estimated TDS using the cementation-exponent and dual-water methods showed a reasonably accurate correlation to measured values. A median error of about 50 percent for all 43 wells is significantly less than typical oil-field results (+ 0.5 order of magnitude) and is within the range of error for most fresh water studies (less than 100 percent) - especially considering that the measured TDS of the data set used for this study ranged from less than 500 mg/l to more than 100,000 mg/l.

Improved accuracy is obtained with the cementation-exponent method by using a more representative porosity value, the effective porosity, and an empirically derived cementation exponent. A total porosity value (from a neutron or density log) and a constant cementation-exponent value can be used in the equation; however, data obtained by the GWRP indicates that for most types of formations, a significant reduction in accuracy occurs. In the dual-water method, improved accuracy is obtained by correcting the initial apparent resistivity of water (R_w) for the effect of bound water on the surface of clay particles. Although the accuracy is high, both methods require the use of computerized algorithms and an iterative solution. Consequently, the cementation-exponent and dual-water methods, as described in this report, are not quick, field-applicable methods to estimate TDS.

The accuracy of the ratio method was found to be less than the cementation-exponent and dual-water methods by at least a factor of 2 (that is, twice the median percent error). An accuracy of $\pm$ a factor of 2 may be acceptable in many cases, such as the field application in this study to determine better quality water-bearing zones prior to well completion. The accuracy of the equation appears to be sensitive to the degree and nature of mud invasion, which can affect the true value of R_{mf}. Factors affecting R_{mf} are numerous, including the nature of mud additives, the nature of the natural mud-creating clays and/or formation matrix, or the chemistry of the formation water and/or initial drilling water. Under certain conditions, the ratio method may be a better choice to estimate TDS than either the cementation-exponent or dual-water methods; the principal advantages being that parameters can be read directly from the logs in the field, a nuclear porosity log is not required, and TDS can be estimated without complex algorithms and iterative solutions as needed by the other two methods.

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Variable Hydraulic Responses Observed in the Alluvial Aquifer of Eastern Abu Dhabi Emirate

Eric Silva

VARIABLE HYDRAULIC RESPONSES OBSERVED IN THE ALLUVIAL AQUIFER OF EASTERN ABU DHABI EMIRATE

Eric Silva
National Drilling Company
Al Ain, United Arab Emirates

ABSTRACT

The Ground-Water Research Project, a cooperative study by the National Drilling Company of Abu Dhabi and the United States Geological Survey, has evaluated the hydraulic response of the alluvial aquifer near Al Ain. The alluvium extends west from the Oman Mountains beneath thick dunes for a distance of about 40 kilometers east of the mountain front. The alluvial aquifer is composed of loosely cemented gravel that is as much as 50 meters thick in buried paleowadi channels. The middle part of the channelized gravel is the major ground-water source in the region, especially where dissolution has removed secondary calcite cement.

Wells drilled in the channelized gravel beds display variable specific capacity, which is not consistent with the aquifer composition, hydraulic conductivity, and saturated thickness. In one group of tests, the observation-well drawdown and recovery on semilogarithmic scales are curves with several straight-line segments that increase in slope with time and cannot be analyzed by standard graphical methods. In a second group, depending on the duration of the test, two or more straight-line segments occur with slopes that decrease with time. A third group of tests demonstrated no obvious segmentation in the semilogarithmic plot of the hydraulic response.

The data for pumping tests conducted since 1980 at three well fields were reanalyzed to gain a better understanding of the hydraulics of the alluvial aquifer. The shapes of the semilogarithmic plots of drawdown and recovery curves were compared. Where the ratio of the storage coefficient derived from the pumping and recovery phases was equal to or greater than 1, the test was deemed acceptable. Where the ratio was less than 1, water-level changes in observation wells were considered to be complicated by changes in the aquifer conditions during the tests, namely, transition from confined to unconfined conditions as the aquifer was dewatered.

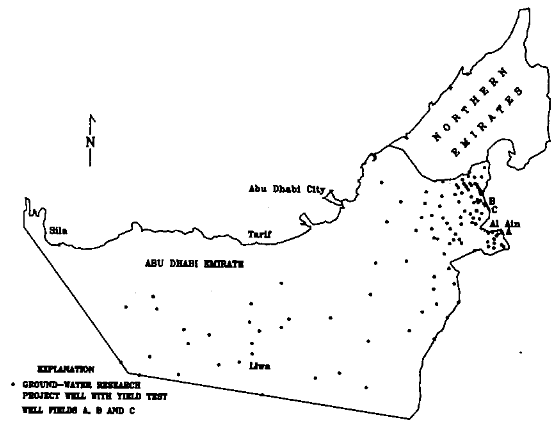
INTRODUCTION

The alluvial aquifer of eastern Abu Dhabi Emirate is a major source of water for domestic agricultural, and industrial supply. A large number of pumping tests have been conducted to assess ground-water availability, determine flow characteristics, evaluate hydrologic conditions, design wells, and develop management strategies (fig. 1). In previous studies, investigators have evaluated pumping tests on a site specific basis rather than evaluating aquifer characteristics on a regional scale (Halcrow, 1969; Gibb, 1970; GeoConsult, 1985). Regional evaluation of aquifer characteristics has been hampered by large variations in test results between well fields and even between well sites in a single well field. Results of numerous tests indicated confined to unconfined storage coefficients ranging between 0.0001 and 0.1 and transmissivity values ranging between 10 and 10,000 m^2/day . These ranges are much larger than expected for the alluvial aquifer. Consequently, standard analytical methods used to evaluate pumping tests may not be the most appropriate.

In 1988, the National Drilling Company of Abu Dhabi and the United States Geological Survey began a Ground-Water Research Project (GWRP) to evaluate the hydrology of Abu Dhabi Emirate. By 1997, the GWRP had constructed more than 230 wells, and of these, about 150 were tested for yield and sampled for analysis of water quality. Variations in hydraulic properties were noted in many tests of wells completed in the alluvial aquifer. Evaluation of results of the tests was difficult because of insufficient observation well data and short duration's of pumping tests. It was recognized that predevelopment pumping tests in the alluvial aquifer provided more reliable indications of aquifer characteristics than more recent tests, which were affected by interference from nearby pumping wells. For this study, data from about 50 pumping tests conducted since 1980 were considered in order to explain large variations in analytical results for wells completed in the alluvial aquifer.

THE AQUIFER

The alluvial aquifer consists of an upper layer of silt and sand, a middle layer of sand and gravel, and a lower layer of gravel in a clay matrix. The middle sand and gravel layer is cemented by carbonate which has been differentially dissolved by ground water. The middle layer is the most significant waterbearing unit in the sequence. The alluvium extends as a blanket from the Oman Mountain front westward about 40 kilometers.



The Figure 1. Approximate locations of wells with pumping tests and well fields A, B, and C.

The aquifer generally is about 25 meters thick, however, it may reach thicknesses of 50 meters in buried paleowadi channels. About 70 percent of the saturated thickness is variably-cemented and differentially-dissolved gravel beds. Wells that penetrate the cemented gravel have a large range of specific capacities, which cannot be explained solely on the basis of variations in saturated thickness or lithology.

DATA ANALYSIS

Data from selected pumping tests were plotted and evaluated. Most tests were for single wells, however, several tests were conducted with observation wells. Drawdown curves were placed into 3 groups based on the shapes of the data plots. For illustrative purposes, tests of the alluvial aquifer at three well fields (A, B, and C in fig. 1) represent the groups (fig. 2).

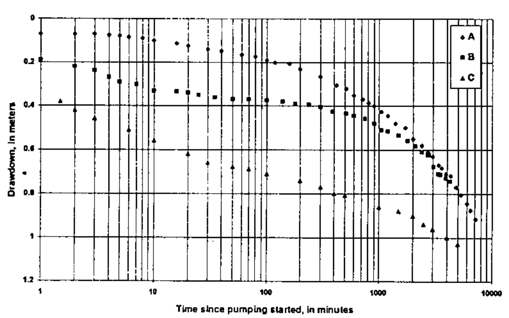


Figure 2. Pumping-test drawdown plots for A, B, and C well fields.

Drawdown curves for Group 1 wells have segmented slopes that increase with time. This group is represented by a drawdown curve at well field A during a five-day test. The curve clearly illustrates a continued increase in slope of segments as pumping duration increases. Because transmissivity is usually calculated based on the slope of the latest straight-line segment, the longer the test in a Group 1 situation, the lower will be the calculated transmissivity.

The drawdown curve representative of Group 2 wells displays a flattening slope followed by a segment of increasing slope. This is the classic curve indicating delayed yield from storage. These features are illustrated in the curve for well field B. Tests for Group 2 have been conducted for as long as 3 days without change in the slope of the last segment.

The drawdown curve for Group 3 wells (well field C) displays segments of increasing slope but much less change than the other groups. The transmissivity calculated from any straight-line segment approximates the transmissivity calculated from a straight line fit to the entire data plot.

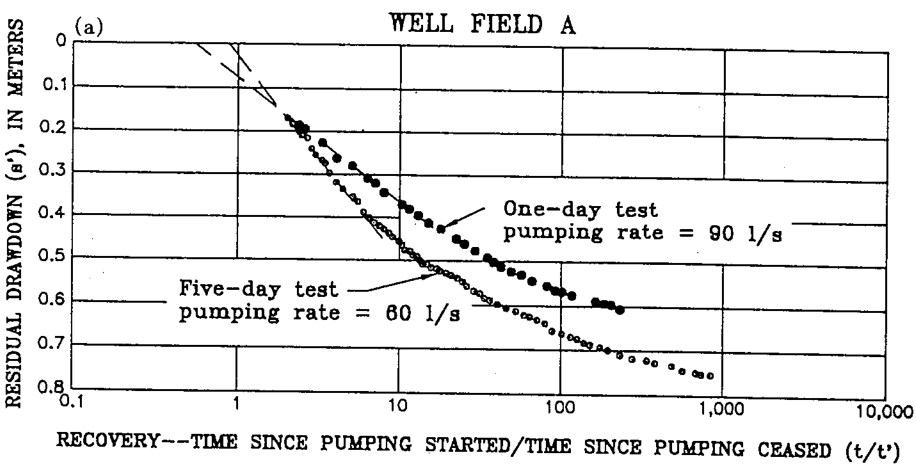
Common methods can be applied to evaluate the results of each test to obtain estimates of aquifer characteristics. However, for Group 1 tests, because slopes of segments continually increase with time, there is no certainty that drawdown curves from tests can be matched to graphical representations of flow equations. In general, tests are rarely conducted longer than one day and the last segment that is represented by a constant slope is used to obtain a solution using the Jacob method (Cooper and Jacob, 1946, in Kruseman and de Ridder, 1990). Curve matching methods of Boulton (1963) and Neuman (1975) are also used to determine transmissivity and storage coefficient. When the three methods were used to evaluate several tests that had been conducted for more than one time duration, such as a 1-day and a 4-day test of the same well, contradictory results were obtained for the different time durations. The contradictory results were observed even for those tests where assumptions for application of the analytical method were satisfied.

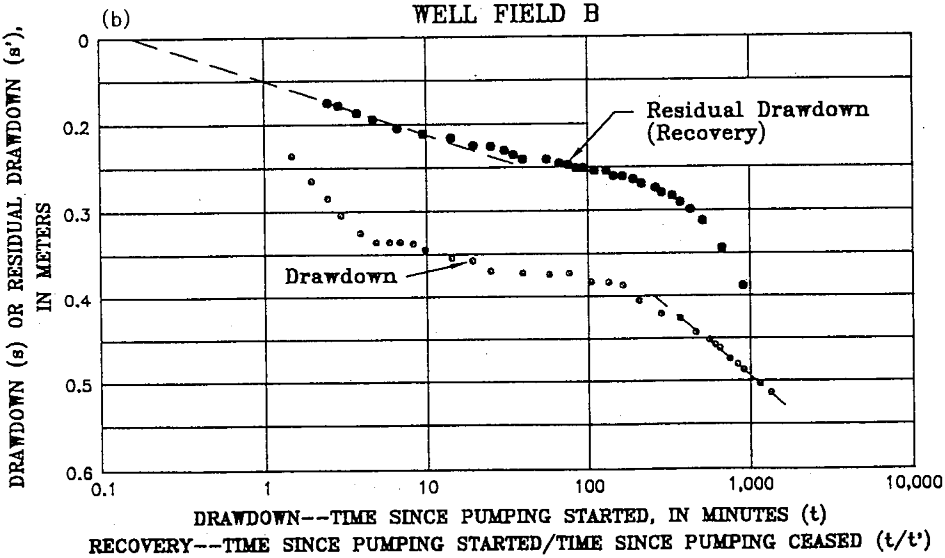
Analyses of recovery data indicate a relation that proves useful in evaluating the pumping tests. Plots of residual drawdown (recovery) data may be more reliable than drawdown data because recovery occurs at a constant rate, whereas a constant discharge during pumping is often difficult to achieve. A study of about 50 tests from wells completed in the alluvial aquifer indicated two distinct conditions. Under one condition (Type X), plots of residual drawdown (s') intersect the time-since-pumping started/time-since-pumping-ceased (t/t') axis at a point less than one ... i.e. $(t/t')_o < 1$. This condition indicates that the water level in a well did not fully recover within the same time period as in which it was lowered. Figure 3 shows recovery plots of this type for tests of wells located in well fields A and B.

Under the second condition (Type Y), plots of recovery data intersect the (t/t') axis at a point equal to or greater than one... i.e. (t/t')o < 1. This condition is illustrated in figure 4, which shows recovery plots for pumping tests for wells located in well fields A, B, and C.

It is apparent that test duration affects the shape of the recovery plots. Figure 3a shows recovery plots for a well in well field A that was tested for one day and for five days. The longer test resulted in a recovery plot that intersects the (t/t') axis at a point nearer to one than the plot for the shorter test. An even longer test would likely result in the recovery plot becoming Type Y instead of Type X.

Length of pumping is not the only factor relating to the aquifer's uncharacteristic response to pumping. Figure 4a shows Type Y conditions for a pumping test conducted in well field A. Drawdown and recovery data were obtained from the same observation well as shown in figure 3a, but caused by pumping a different nearby well. Pumping one well resulted in Type X condition (figure 3a) but pumping a different well resulted in Type Y condition (figure 4a) in the same observation well.





For Type Y conditions, analyses of drawdown and recovery plots using straight-line methods yield similar values for transmissivity. Figures 4a, 4b, and 4c demonstrate that slopes of the late segments of each set of drawdown and recovery curves are comparable. Transmissivities calculated for representative pumping tests for well fields A, B, and C were 1,300, 330, and 1,900 square meters per day, respectively. Storage coefficients calculated from the late segments of drawdown curves for well fields A, B, and C were 0.04, 0.02, and 0.003, respectively.

For Type X conditions, late segments of drawdown and recovery curves are not comparable (fig. 3b). Therefore, applying the straight-line method of analysis would be inappropriate and results would be unreliable.

DISCUSSION

It was shown that the water-level change in the alluvial aquifer in response to pumping may be of two types that can be determined from the recovery plot. The intercept of the recovery segment at points where $(t/t')o < 1$ or $(t/t')o > 1$ can be related mathematically to the ratio of the storage coefficient calculated for the pumping phase (S_P) and the recovery phase (S_R). According

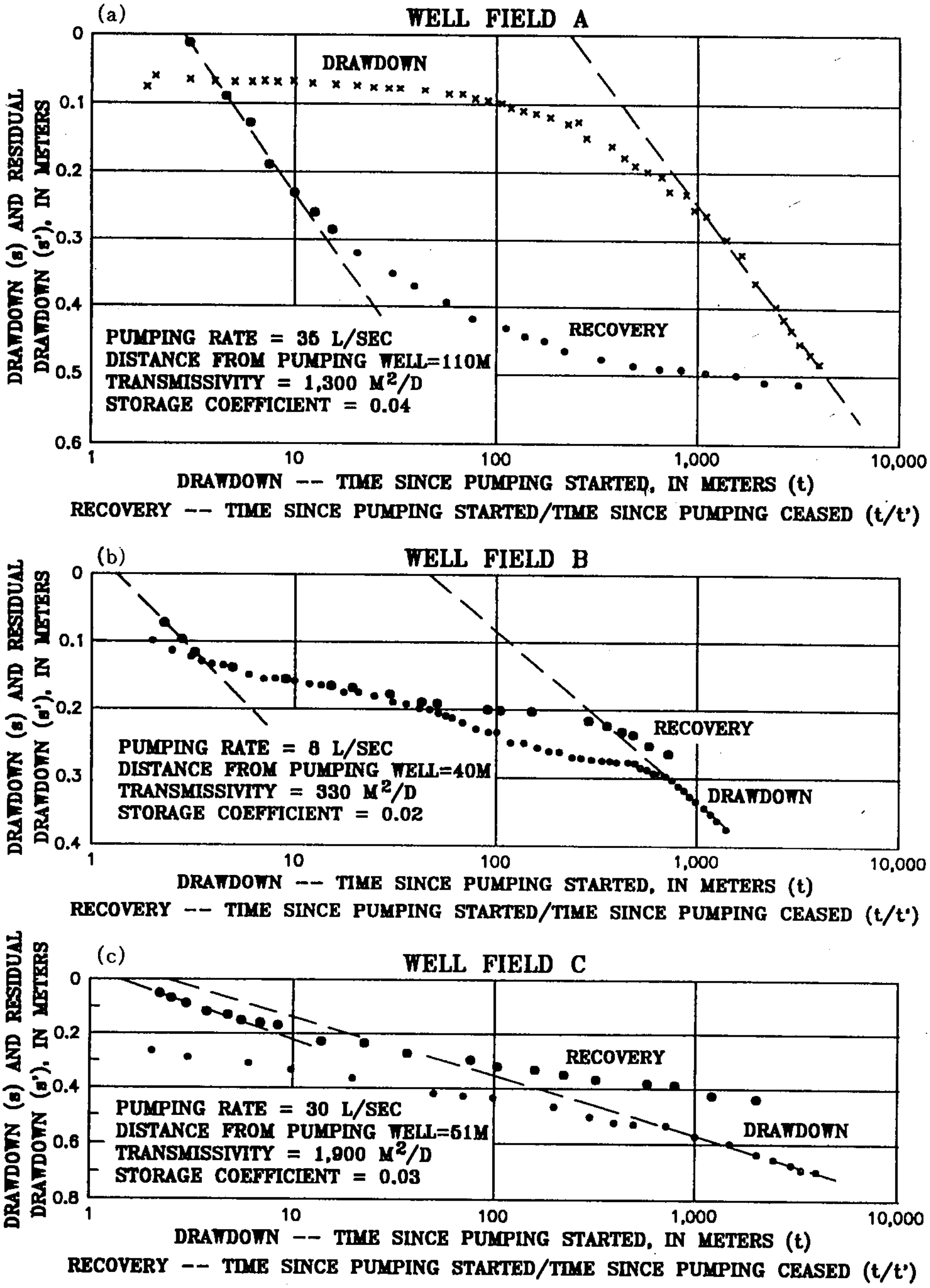


Figure 4. Pumping-test condition (Type Y) where a straight line on the recovery plot intercepts the (t/t') axis at a point equal to or greater than 1.

to Theis (1935, in Kruseman and de Ridder, 1990) the residual drawdown after a pumping test with a constant discharge is:

$$s' = \frac{Q}{4\pi T} W(u) - W(u')], \tag{1}$$

where $$u = \frac{r^2 S_p}{4Tt} \text{ and } u' = \frac{r^2 S_R}{4Tt'} \tag{2}$$

When u and u' are sufficiently small, equation 1 can be approximated as:

$$s' = \frac{Q}{4\pi T} [\log \frac{4Tt}{r^2 S_p} - \log \frac{4Tt'}{r^2 S_R}] \tag{3}$$

where

- s' = residual drawdown measured in the observation well, in meters,
- r = distance from pumping well to observation well, in meters,
- T = aquifer transmissivity, in square meters per day,
- S_R = storage coefficient from recovery phase,
- S_p = storage coefficient from pumping phase,
- t = time since the start of pumping, in days,
- t' = time since pumping ceased, in days, and
- Q = pumping rate, in cubic meters per day.

When S_p and S_R are constants but unequal and transmissivity is constant, the straight line through the plotted points intercepts the time axis where:

$s' = 0$ at a point $(t/t') = (t/t')o$.

At this point equation (3) becomes:

$$0 = \frac{2.30}{4\pi T} [\log(t/t')_0 - \log (S_p/S_R)]. \tag{4}$$

Because $\frac{2.30}{4\pi T} \neq 0$,

$[\log(t/t')_0 - \log(S_p/S_R)] = 0$, and

$$(t/t')_0 = S_P/S_R \tag{5}$$

If $(t/t')_0 < 1$, then $S_P/S_R > 1$,

and $S_p > S_R$

If $(t/t')o < 1$, then $S_P/S_R < 1$,

and $S_p > S_R$

The shapes of the drawdown and recovery curves reflect the relative storage change. Very gently segmented curves represent a condition where $S_p/S_R > 1$. The C well field can be considered as an example for this condition (figs. 2 and 4c). The segmented lines or curves showing change in gradients with time of pumping or duration of tests represent an unstable temporary condition where $S_p/S_R < 1$ on recovery plots.

This temporary situation may or may not change within a practically acceptable pumping period (5 days) depending upon the heterogeneity of the aquifer. This can be clearly understood by comparing the results of two 5-day tests conducted in well field A. As mentioned previously the water level in one observation well responded differently to pumping from two different pumped wells. In the case illustrated for well field A, shown in figure 2, the slope of the drawdown curve continued to increase as duration of pumping increased. As shown on figure 3a, recovery plots illustrate that $S_P/S_R < 1$. However, during a second test using a different pumped well, the drawdown and recovery plots for the observation well demonstrate that $S_p/S_R > 1$ for a 5-day test. In the first case, the Jacob method cannot be used to determine transmissivity. In the second case where $S_p/S_R > 1$, the Jacob method can be applied to the drawdown plot to obtain transmissivity and storage coefficient. The only difference between the two tests was the location of the pumping well, which demonstrates that heterogeneity of the alluvium is a contributing factor in the aquifer's response to pumping.

The condition where $S_p/S_R > 1$ for an acceptable period of test duration, provides an opportunity to apply the Jacob method to determine the transmissivity and storage coefficient. The condition where $S_p/S_R > 1$ suggests further that flow can be described as simple Darcian flow, uncomplicated by other factors. Similarly the condition where $S_p/S_R > 1$ suggests that there is a factor or many factors shadowing the Darcian flow during the full length of the test. That the change from $S_p/S_R < 1$ to $S_p/S_R > 1$ occurred in repeated tests depending on duration of pumping and locality, indicates that the factor or factors shadowing the Darcian flow are temporary depending on the heterogeneity of the alluvium. These factor(s) could be related to delayed yield, heterogeneity, or to both. Other factors could relate with the delayed yield indirectly. The relation between the shapes of the drawdown curves and different confining conditions indicated by the differences in storage coefficient could be one factor associated with delayed yield, but requires further research for confirmation. The storage coefficient values 0.003, 0.02, 0.04 calculated for the three examples indicate an intermediate condition of confinement. Unconfined aquifer storage coefficients are typically on the order of 0.2 and confined aquifer storage coefficients are on the order of 0.0001. The intermediate values calculated from tests at well fields A, B, and C may represent the change from confined to unconfined conditions in the alluvial aquifer as a number of permeable zones are dewatered.

CONCLUSIONS

Pumping tests of wells completed in the alluvial aquifer in the far eastern part of Abu Dhabi Emirate display variable responses depending on certain factors that govern dewatering of the aquifer. In many tests, it appears that Darcian flow is affected, and reflected in the semilogarithmic recovery plot by the condition that $S_P/S_R < 1$. That Darcian flow is not affected, is reflected in the recovery plot by the condition that $S_P/S_R > 1$ and a late straight-line segment of constant gradient. In the pumping phase straight-line segments can be used to calculate transmissivity and storage coefficient, and a parallel segment in the recovery phase would confirm the values. For pumping tests where water-level measurements in observation wells indicate the condition $S_P/S_R < 1$, reliable estimates of transmissivity and storage coefficient cannot be obtained by standard analytical methods. The tests should be repeated for a longer period or the direction between pumping and observation well changed. Reliable results may be obtained when $S_P/S_R > 1$ as confirmed from the recovery plot. The factors that govern dewatering of the aquifer are complicated and require research into new methods for test analysis.

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Application of the Eden-Hazel Method for Determining Transmissivity from Step-Test Recovery Data

Mustafa Al Amin Nasr

APPLICATION OF THE EDEN-HAZEL METHOD FOR DETERMINING TRANSMISSIVITY FROM STEP-TEST RECOVERY DATA

Mustafa Al Amin Nasr
National Drilling Company
Al Ain, United Arab Emirates

ABSTRACT

Step-drawdown data are often used to estimate well efficiency, specific capacity of the well, and determine the optimal pumping rate for constant discharge tests. However, aquifer transmissivity is not generally determined from the same data, though several analytical procedures are available. Analytical procedures can also be used to estimate transmissivity from recovery data collected after the final discharge step of the test. One procedure, the Eden-Hazel method, was applied to determine transmissivity from step-test recovery data collected at 30 water wells in the Emirate of Abu Dhabi, United Arab Emirates. This procedure does not require additional pumping, only the additional time necessary to measure the water-level recovery in the well following the step-drawdown test. The water wells were constructed by the Ground-Water Research Project - a cooperative program between the National Drilling Company and the U.S. Geological Survey to study fresh to slightly saline (total dissolved-solids concentration less than 15,000 milligrams per liter) water-bearing formations in the Emirate of Abu Dhabi.

Transmissivities estimated using the Eden-Hazel method were compared to those estimated from constant-discharge drawdown and recovery data using the standard straight line, semi-log method of analysis. The step and constant-discharge data were collected from single, partially penetrating wells in an unconfined aquifer; consequently, the "apparent" transmissivities determined from the analyses do not strictly meet all of the Theis assumptions for analysis of confined aquifer hydraulic properties. However, estimated apparent transmissivities using the Eden-Hazel method fell within 10 percent of the values determined from constant-discharge recovery tests in 24 of the cases. Results of this evaluation were useful in developing more efficient and economical aquifer testing procedures for the project.

INTRODUCTION

The Ground-Water Research Project for Abu Dhabi Emirate is a cooperative investigation between the National Drilling Company of Abu Dhabi Emirate and the United States Geological Survey. The Project is conducting a systematic evaluation of the groundwater resources of the Emirate. The Project began in 1988, and by mid-1996, 226 wells had been constructed and pumping tests had been conducted in 165 wells. Pumping tests generally consisted of a step-drawdown test followed by a constant-discharge test. This report describes a method not commonly used for analysis of pumping tests, but was successfully employed by the Ground-Water Research Project to validate analyses made using standard methods.

The step-drawdown test, in which a well is pumped at a minimum of three rates in succession, is a frequently performed type of pumping test, particularly in the case of a single well. It is usually conducted to determine the behavior of the well, evaluate well and formation losses, and evaluate well efficiency.

Standard methods for analysis of a step-drawdown test focus on relative changes in drawdown that are observed during the pumping phase of the test. Eden and Hazel (1973) developed a method for calculating aquifer transmissivity using recovery data from a step-drawdown test. The method is based on a straight-line approximation similar to that commonly used for analysis of drawdown and recovery for a constant-discharge test. Recovery measurements allow the evaluation of transmissivity of the aquifer, thereby providing an independent check of the results of any subsequent long-term constant-discharge pumping test. Furthermore, analysis of the recovery data may be more reliable than analysis of the pumping data, especially in the pumping well where measurements may be affected by well losses and surging.

EDEN-HAZEL METHOD

The general assumptions and conditions underlying the Eden-Hazel method for analysis of recovery data are:

1. The aquifer is confined;
2. The aquifer has seemingly infinite areal extent;
3. The aquifer is homogeneous, isotropic, and of uniform thickness over the area influenced by the test;
4. The aquifer is pumped in three or more steps with significant increase in pumping rate;
5. Prior to pumping, the piezometric surface is horizontal;

6. The well taps the full thickness of the aquifer;
7. Flow to the well is in an unsteady state;
8. The duration of each pumping step must be long enough to satisfy rules concerning the stability and spread of the cone of depression.

PROCEDURE

— Calculate for the recovery phase the values of H_n using measured discharges and times and the equation:

$$Hn = \sum_{i-1}^{n} \Delta Q \log(t-t_i) \qquad (1)$$

where: $\Delta Q_i = Q_i - Q_{i-1}$ = the discharge increment beginning at time t_1, in cubic meters per minute;
t = time since pumping started, in minutes;
t_i = time at which the i-th step begins, in minutes.

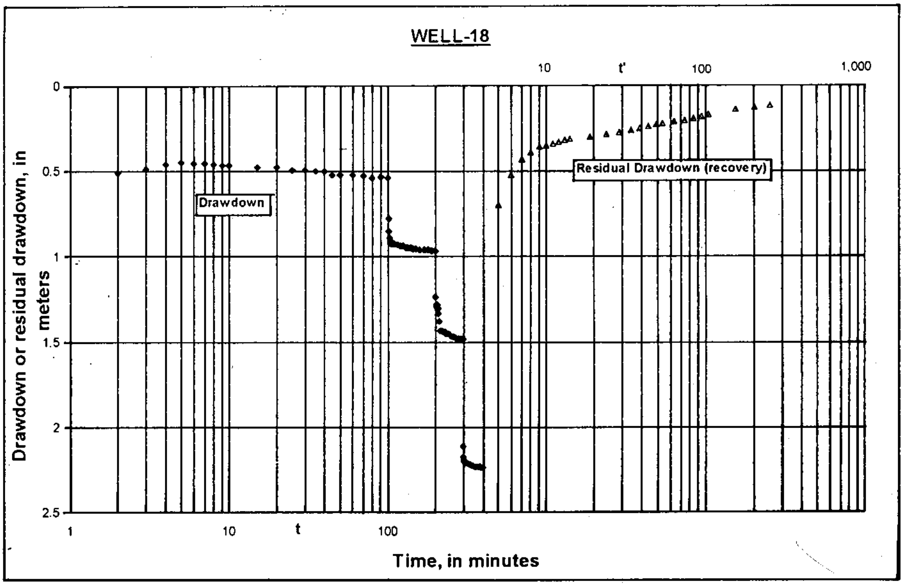
— On arithmetic paper, plot the observed residual drawdown $s'_{w(n)}$ versus the corresponding calculated values of H_n.

— Draw a straight line through the points and determine the slope, $\Delta s'_{w(n)} / n$

— Calculate transmissivity using the Jacob straight-line approximation of the Theis equation: $T=2.30 / 4\pi(\Delta s'_{w(n)} / \Delta H_n)$ (2)

EXAMPLE

The analysis of transmissivity by the Eden-Hazel recovery method as described in Kruseman and de Ridder (1990, p. 233-235) is demonstrated for Ground-Water Research Project Well-18 located in central Abu Dhabi Emirate. The well is completed in a fine- to medium-grained sand aquifer and has 35 meters of screen distributed at intervals between depths of 30 and 89 meters below land surface. The well was pumped at four stepped rates ranging from 200 to 930 m^3/d with step intervals of 100 minutes. Figure 1 shows plots of the drawdown and recovery. The test schedule, calculated values and plot of H_n versus $s'_{w(n)}$, and example calculations of H_n and T are presented in figure 2. The calculated transmissivity is 1,050 m^2/d.



Step#	Step1	Step2	Step3	Step4
Q, in m³/d	206	398	591	929
time, in minutes	100	200	300	400

$t'_{(min)}$	$t_{(min)}$	H_n	$s'_{w(n)}$	$t'_{(min)}$	$t_{(min)}$	H_n	$s'_{w(n)}$
3	403	1.177	0.43	35	435	0.536	0.25
4	404	1.098	0.39	40	440	0.505	0.24
5	405	1.038	0.36	45	445	0.478	0.23
6	406	0.988	0.35	50	450	0.455	0.22
7	407	0.946	0.34	60	460	0.416	0.21
8	408	0.911	0.33	70	470	0.384	0.21
9	409	0.879	0.32	80	480	0.357	0.20
10	410	0.851	0.32	90	490	0.334	0.18
15	415	0.745	0.30	100	500	0.315	0.17
20	420	0.672	0.29	150	550	0.246	0.14
25	425	0.617	0.27	200	600	0.203	0.13
30	430	0.572	0.26	250	650	0.174	0.12

Example calculation of Hn2 for the 4th measurement:

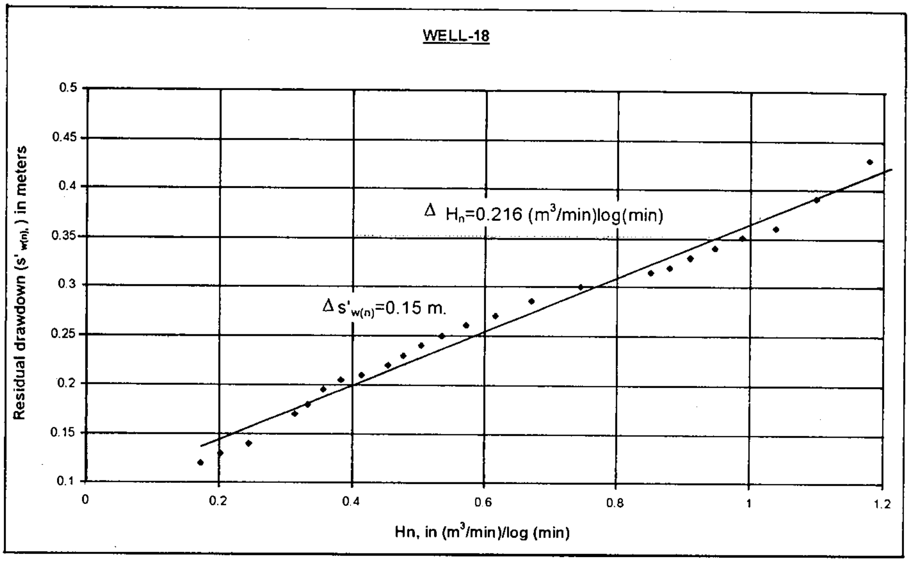


Figure 2. Example analysis of step-drawdown test data using the Eden-Hazel recovery method

An independent check of transmissivity was made by conducting a 5-hour constant discharge test of the well at a rate of 882 m^3/d and analyzing results by the standard straight-line method commonly used by hydrologists. The plot of drawdown and recovery and the results of the analysis are shown in figure 3. The calculated transmissivity is 1,095 m^2/d from the drawdown segment and 1,110 m^2/d from the recovery segment.

The transmissivity calculated by the Eden-Hazel method using data from the recovery of a step-drawdown test compared favorably with transmissivities calculated by the standard straight-line method using data from recovery of a constant-discharge test. It should be noted that the pumping rate for the constant-discharge test fell within the range of pumping rates for the step-drawdown test.

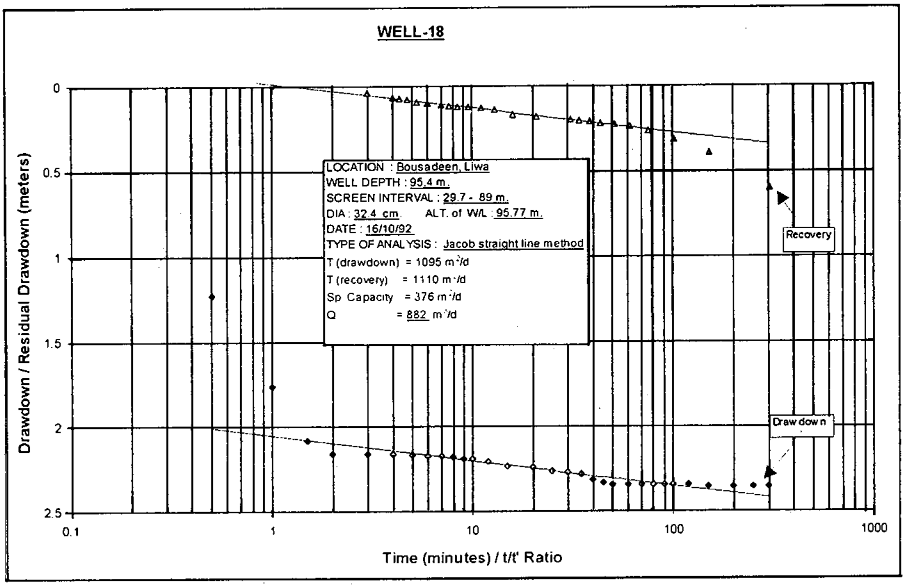


Figure 3. Straight-line method of analysis for a constant-discharge test of Well-18.

APPLICATION

The Eden-Hazel recovery method (Kruseman and de Ridder, 1990) was used to verify the transmissivity calculations made by the straight-line method for constant discharge tests conducted by the Ground-Water Research Project. Table 1 lists results for 30 tests for which pairs of step-drawdown and constant-discharge test data were collected. By comparison, the transmissivity calculated from recovery of the step-drawdown test ranged from 57 percent below to 36 percent above that calculated from recovery of the constant-discharge test. The difference tended to be greater for tests in the lower third of the transmissivity range, below about 200 m^2/d. The transmissivity comparisons are displayed graphically in figure 4. The high correlation indicates that transmissivity graphically in figure 4. The high correlation indicates that transmissivity calculated from recovery of the step-drawdown test matches that from a constant-discharge test.

Table 1. Transmissivities at selected Ground-Water Research Project sites calculated using standard and Eden-Hazel methods (m^2/d, square meters per day; SDT, step-drawdown test; CDT, constant-discharge test)

Well number	Transmissivity (m^2/d)		Percent difference
	SDT	CDT	
Well-1	8,448	8,615	2
Well-2	8,060	8,430	4
Well-3	3,385	3,131	-8
Well-4	30	29	-3
Well-5	68	62	- 10
Well-6	161	171	6
Well-7	119	116	-3
Well-8	221	345	36
Well-9	242	235	-3
Well- 10	2,480	2,463	- 1
Well-11	28	30	7
Well-12	160	180	11
Well-13	69	69	0
Well-14	197	201	2
Well-15	346	346	0
Well- 16	1,791	1,665	-8
Well- 17	961	928	-4
Well- 18	1,050	1,110	5
Well-19	3,374	3,277	-3
Well-20	902	893	- 1
Well-21	1,021	1,279	20
Well-22	1,072	1,015	-6
Well-23	3,062	2,997	-2
Well-24	772	798	3
Well-25	3,570	3,696	3
Well-26	108	95	-14
Well-27	1,093	1,112	2
Well-28	510	656	22
Well-29	33	21	-57
Well-30	193	196	2

Percent difference calculated as ((CDT-SDT)/CDT) x 100

Single, partially penetrating wells in an unconfined aquifer; consequently, the "apparent" transmissivities determined from the analyses do not strictly meet all of the Theis assumptions. For example, tests in an unconfined aquifer usually should be conducted for several days rather than for several hours to insure drainage within the cone of depression. However, estimated apparent transmissivities using the Eden-Hazel method compared favorably to apparent transmissivities determined from constant-discharge tests.

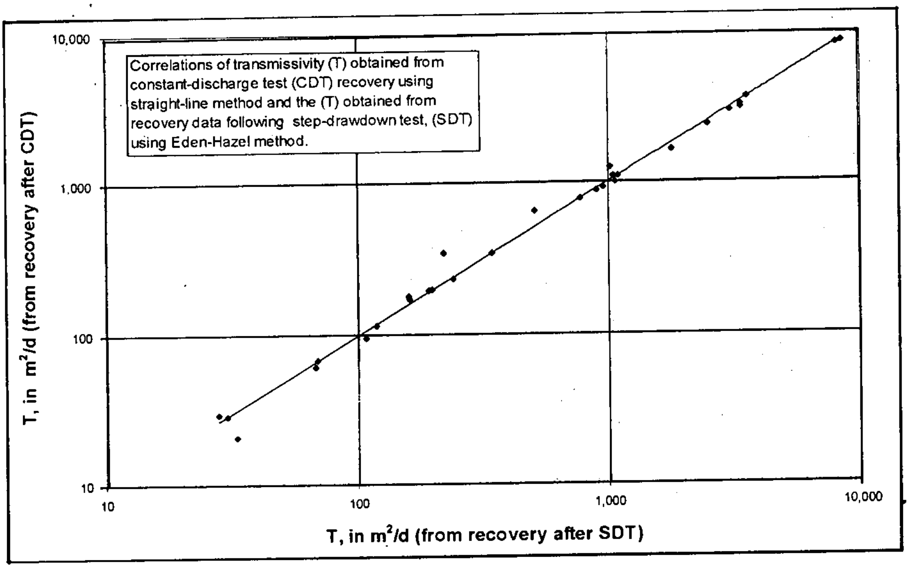


Figure 4. Correlation of transmissivities calculated by the Eden-Hazel recovery method for step-drawdown tests and the straight-line recovery method for constant-discharge tests.

SUMMARY AND CONCLUSIONS

The cooperative Ground-Water Research Project for Abu Dhabi Emirate has conducted 165 single-well yield tests to estimate hydraulic properties of the unconfined surficial aquifer. Results of 30 tests were verified using the Eden-Hazel recovery method for calculating transmissivity from the water-level recovery measured at the end of a stepdrawdown test. The primary goals of the step-drawdown test were to calculate well efficiency and well loss. Transmissivity calculated by the Eden-Hazel method fell within 10 percent of that from recovery of the constant-discharge test in 24 of the cases. The good correlation does not preclude the running of future constant-discharge tests by the Project, however, because the step-drawdown test is always conducted beforehand, the Eden-Hazel recovery method is recommended as a check. The method is recommended as a substitute analysis if for some reason the constant-discharge test can not be conducted.

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Numerical Simulation and Experimental Validation of Dual Porosity/Dual Permeability Flow

Tariq Cheema and M. Rafiq Islam

NUMERICAL SIMULATION AND EXPERIMENTAL VALIDATION OF DUAL POROSITY/DUAL PERMEABILITY FLOW THROUGH FRACTURED FORMATIONS

Tariq Cheema and M. Rafiq Islam*
Department of Earth Sciences, Sultan Qaboos University,
Muscat, Sultanate of Oman
*Department of Petroleum Engineering,
United Arab Emirates University, Al-Ain, U.A.E.

ABSTRACT

The presence of fracture is associated with high water productivity as well as high contaminant vulnerability. Consequently, it is important to develop a technique for properly modeling fractured formations. This paper presents numerical simulation results of fluid flow in a fractured formation with the dual-porosity, dual-permeability approach. Numerical simulation results are compared with experimental results, obtained from a dual-porosity, dual-permeability model as well as a parallel plate model. Because experiments were conducted with elegant but realistic boundary conditions, the comparison between experimental and numerical results offers validation of the numerical model. A method is proposed for possible use of experimental data in numerical simulators in order to minimize expensive field tests, commonly conducted to generate similar data. Finally, results of a series of numerical runs are discussed in order to identify the role of fracture width, fracture thickness, fracture spacing, matrix permeability and scaling factors. The proposed method can be applied to predict anisotropic hydrologic behaviour of some of the fractured formations of the Arabian Peninsula.

Keywords: Hydrogeology, Groundwater flow through fractures, Dual porosity, Experimental and numerical modelling.

INTRODUCTION

Fractured rocks are highly heterogeneous. Depending on the degree of heterogeneity, different flow models can be conceptualized. In a dual-porosity model, one porosity represents the rock matrix and the second represents that of the fracture networks. In general, fracture storage capacity is low and fracture transmissivity is high. If both the fracture and matrix have continuity and the matrix transmissivity is significant, the model is considered as the dual permeability model. For single phase flow, the mathematical model for the dual porosity model is based on the work done by Barenblatt et *al*. [1960]. The reservoir can be visualized as a set of stacked sugar cubes [Warren and Root, 1960], parallel layers separated by horizontal fractures or a set of vertical match stick columns. In reality, the fracture spacing and distribution vary throughout the reservoir [Kazemi and Gilman, 1993].

Ever since the early work by Barenhlatt et al. [1960] and Warren and Root [1960], there have been numerous studies reported on modeling fractured formations with the dual-porosity approach [Gilman and Kazemi, 1983]. In this approach, every fractured grid block is subdivided into two regions: a fractured region with high permeability and low storage volume, and the reservoir rock (matrix) with low permeability and high storage volume. The fractures provide the main path for fluid flow whereas the matrix acts as a source or sink to the fractures. In the standard dual porosity approach, there is no communication between matrix blocks in the fractured region. Refinements of the dual porosity concept involve the division of the matrix blocks into several grid blocks [Pruess and Narasimhan, 1988; Gilman, 1986] and the connection between matrix blocks (dual porosity/dual permeability) in the fractured region [Hill and Thomas, 1987; Gilman and Kazemi, 1988]. It has been shown that refinement improves the predictions of transient phenomena and gravity segregation in matrix blocks.

Despite increasing recognition of numerical models of fractured formations, little has been done to experimentally validate any of these modeling approaches. It is important to compare numerical results with those of experiments, conducted under controlled boundary conditions. This study presents both experimental and numerical results of a dual porosity, dual permeability system. The numerical simulator helps identify controlling parameters and, in turn, helps develop a better technique for modeling fluid flow in fractured porous media.

GOVERNING EQUATIONS

For a dual porosity, dual permeability porous medium, the governing equation for a single-phase, Newtonian fluid is given in the following tensorial form [Bai et al., 1993]:

$$-\frac{1}{\mu}k_m p_{m,kk} = \phi_m \dot{\varepsilon}_{kk} - \phi_m^* \dot{p}_m \pm \xi(\Delta p)$$

In the above equation, μ is the fluid dynamic viscosity, km is permeability of the phase m, pm is the pressure of the phase m, is the pressure ratio factor of the phase m, * is the relative compressibility, and ξ is fluid transfer rate between matrix and fracture (need not be isotropic). For a non-deforming matrix, equation (I) assumes the following forms for two-dimensional flow:

$$\frac{1}{\mu}\left(k_{1x}\frac{\partial^2 p_1}{\partial x^2}+k_{1y}\frac{\partial^2 p_1}{\partial y^2}\right)=\phi_1^*\frac{\partial p_1}{\partial t}+\xi_1(p_1-p_2)$$

$$\frac{1}{\mu}\left(k_{2x}\frac{\partial^2 p_2}{\partial x^2}+k_{2y}\frac{\partial^2 p_2}{\partial y^2}\right)=\phi_2^*\frac{\partial p_2}{\partial t}+\xi_2(p_1-p_2)$$

In the above equations, the subscript.s 1 and 2 represent the matrix and the fracture media, respectively. Equations (2) and (3) have only two unknowns, p_1 and p_2. These two equations are solved using the following numerical scheme.

NUMERICAL SOLUTION METHOD AND INPUT DATA

The governing equations (2) and (3) were discretized using finite difference with fully implicit formulation. The resulting set of algebraic equations were solved iteratively using the successive over-relaxation scheme. A grid system of 40x40 was used throughout the numerical study. A time step of 1 second was used for modeling laboratory results, whereas a time step of 100 seconds was used for modeling field performance (predictive runs). Basic data supplied from experimental studies were initial and final boundary conditions, average fracture width, formation geometry, average fracture spacing and fracture anisotropy. Note that laboratory experiments were conducted using anisotropic matrix properties while maintaining a given fracture anisotropy, dictated by the orientation of the fractures of the system.

Table 1 gives dimensions of the physical model, along with petrophysical properties of the experimental model. These values, along with the absolute permeability of the matrix, were generated through experimental measurements. The rate of fluid transfer from value of ξ was calculated using the following expression [Kazemi and Gilman, 1993]

$$\xi = \frac{\alpha k_1}{\mu}$$

where α is the shape factor, given by the following relationship [Kazemi and Gilman, 1993]

$$\alpha = 8\left(\frac{1}{L_x^2}+\frac{1}{L_y^2}+\frac{1}{L_z^2}\right).$$

In the above expression the matrix medium is considered to be a rectangle of dimension Lx, Ly, and Lz. For a system for which the fractures do not intersect orthogonally, α can assume different values. However, the best value of α should be determined experimentally if the angle of inclination of different fractures vary. Matrix permeability was calculated directly through experimental measurements, the fracture permeability in the direction parallel to the fracture set was determined using parallel plate analogy, given by

$$k_2 = \frac{b^2}{12}$$

where *b* is the fracture width.

Table 1. General experimental data

Fracture width	1.0 mm (Madison) 0.5 mm (Windcave) 0.9 mm (Rapid City)
Average Fracture spacing	7 cm (Madison) 2.9 cm (Rapid City) 2.2 cm (Windcave)
Length of the model	0.29 m
Width of the model	0.29 m
Thickness of the model	0.3 mm
Viscosity of water	0.001 kg/m/s (=1 cp)
Pressure in the direction of flow	5788 Pa
Pressure at the left boundary	107652 Pa
Pressure at the right boundary	101864 Pa
Matrix permeability	5.20 10-10 m^2
Relative compressibility of the matrix	2.678 10^{-9}
Relative compressibility of the fracture	3.159 10^{-9}

EXPERIMENTAL PROCEDURE

Several sites of the Madison and Minnelusa formations, located in the Black

Hills region of South Dakota, were selected as the prototype. Geology of these formations have been described in detail by Cheema and Islam [1994]. Initially fracture trace maps were constructed for the areas of study. The presence of the fractures in the formation was verified with the Ground Probing Radar and resistivity survey. Major trends of fracture traces were also compared with actual fractures by statistical analysis [Cheema and Islam, 1994a]

Two dimensional models were used for the laboratory tests conducted in this study. A square flow cell with 15 inch each side was constructed. This flow cell was equipped with 16 outlets/inlets, four on each side of the square, which are connected to the groove through 1/8 inch diameter holes within the body of the cell. The experiment was conducted by taking square regions from the fracture trace map. The square region was then rotated clockwise and at every 22.5° rotation, the fracture trace pattern duly drawn. The fracture trace configuration was then transferred to the impervious vinyl sheet that was cut along the fracture traces. Each piece was then glued firmly to the flow cell. For the dual porosity case, the same procedure was followed except that the impervious vinyl was replaced by a porous polyethylene sheet. The driving force behind the water flow was the hydraulic gradient and this was simulated in the laboratory using different measuring flasks at different levels. A constant head was maintained at the top of each flask. Once the outflow, Qout, was measured, the model was then rotated counterclockwise at an angle of 90°, 180°, and 270° measuring Qout each time. In total, 16 outflow measurements were taken for each study area. The hydraulic conductivity in the direction of the gradient (Kg) was calculated by using the following equation

The resulting $K_g^{-1/2}$ values were plotted against the angle of orientation for each fractured formations modeled. These data were curve fitted using non-linear regression so that the best-fit ellipse emerged.

RESULTS AND DISCUSSION

Numerical experimentation was performed in four stages. Initial experiments were conducted to model flow through a fractured formation for which the matrix permeability is negligible as compared to the fracture permeability (typical parallel plate analogy). The second set of numerical experimentation was conducted to model true dual porosity and dual permeability cases. Then, numerical experimentation was conducted to observe the effect of various parameters. Finally, the scaling up procedure was considered through several runs with field-scale parameters.

Zero Matrix Permeability Case

Initial numerical simulation runs were conducted for modeling fluid flow through fractures only. This particular case was modeled using zero matrix permeability. Experimental tests were performed, however, using impermeable vinyl sheets. Table 2 compares maximum flow rates which were observed in the laboratory model with those predicted by the numerical simulator. In the numerical simulator, the anisotropy value observed in the laboratory were inserted as the ratio of the directional permeabilities, kl_x and kl_y. This approach was found to be more appropriate for modeling parallel plate experiments.

Table 2 and experimental results

Simulated area	Type of model	Equivalent permeability (m²)	Fracture anisotropy	Maximum flow rate, ml/sec (numerical)	Steady-state flow rate, ml/sec (experimental)
Minnelusa	Parallel plate	1.09.10-11 (m²)	4.94	0.128	0.128
Madison	Parallel plate	6.45.10-11 (m²)	1.24	0.053	0.053
Madison+ Minnelusa	Parallel plate	2.64.10-11 (m²)	1.8	0.307	0.307
Rapid City Area	Parallel plate	9.11.10-11 (m²)	1.2	1.04	1.04
Madison	Dual porosity	N.A.	1.24	7.22	7.56
Rapid City Area	Dual porosity	N.A.	2.0	8.02	8.28
Wind Cave	Dual porosity	N.A.	1.8	6.45	6.28

The only adjustable parameter in the modeling was the equivalent permeability of the porous medium. Note that the matrix permeability being zero, one has to deal with equivalent permeability of the fractures. Table 2 shows the equivalent permeability values for different parallel plate experiments. It is expected that due to differences in fracture spacing and orientation, the equivalent permeability is different for different cases.

Dual-Porosity, Dual Permeability Case

For these cases, fracture anisotropy values were taken from experiments conducted under impermeable matrix flow conditions. It was assumed that the matrix itself does not exhibit any directionality in permeability. This assumption was in conformance with the experiments for which an anisotropic porous medium was used as the matrix. Table 2 lists major characteristics and results of the dual porosity experiments along with steady-state numerical predictions. The unsteady-state results for different areas are compared in Figure 1. Note that the experimental observation was made some 40 seconds after the initiation of the experimental runs. Numerical results indicate that the steady state was reached for different cases within 25 seconds of the initiation of the experiments. Even though unsteady-state results were not monitored experimentally, it was observed that initial flow rate were much higher than the steady-state values. The rapid decline of flow rates for all different cases indicate the effectiveness of the numerial model in predicting the unsteadystate behavior. Note that the Wind Cave area took the longest time in reaching the steady state. This area is characterized by the smallest fracture width and the highest fracture frequency. A higher frequency

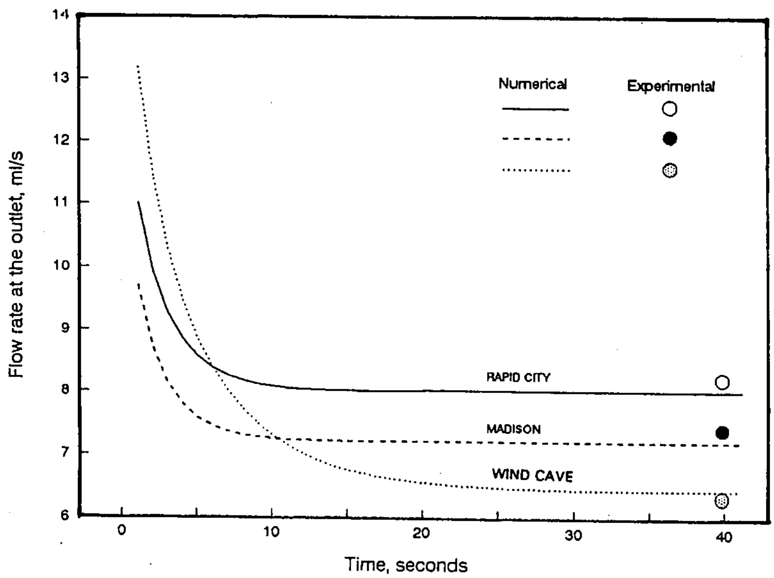

Figure 1. Comparison of experimental and numerical results

contributes to larger surface area over which the matrix/fracture fluid transfer takes place. A larger area corresponds to longer time for reaching equilibrium. Similarly, smaller fracture width leads to lower fracture permeability which retards fluid transfer to and from the fracture as well as through the fracture. The net result of this low fracture permeability is a delay in reaching the steady state.

Effect of fracture width

A series of numerical runs was conducted for different cases in order to study the effect of fracture width. Fracture width plays a significant role is determining the pressure profile and, therefore, the flow rate through the dual porosity, dual permeability system. It is likely that the role of fracture width will change depending on the fracture spacing. Therefore, the effect of fracture width was studied for all three different spacing cases, namely, Madison, Rapid City, and Wind Cave area. Figure 2 shows the effect of fracture width on the Madison model (for a fracture spacing of 7 cm). At lower values of the fracture width, the increase in steady-state flow rate is not as intense as those corresponding to wider fractures. Starting from a fracture width of 0.7mm, the increase in fracture width is drastic. Note that the spacing for the Madison model was quite large (low fracture frequency) and the flow is not expected to be dominated by the fracture unless the fracture width is large.

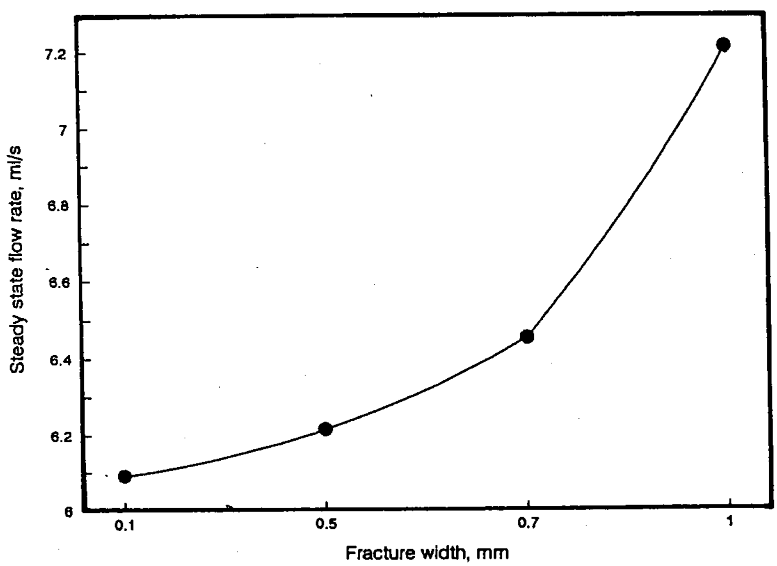

Figure 2. Effect of fracture width on flow rate

Effect of fracture spacing

Figure 3 shows the transient behavior for different spacing values for the Wind Cave region. This particular region had the highest fracture frequency and the lowest fracture width. Note that the quick decline in flow rate during the earlier stages of the flow test persists for all different spacings. Consistently, all cases gradually converge to steady-state solutions. The time required to reach the steady state, however, depends on the spacing. The inset of Figure 3 shows the variation in steady state flow rates with increasing spacing. The flow rate becomes insensitive to the spacing for larger spacing values, following a rapid decline at lower values of the spacing.

Effect of matrix permeability

A series of numerical runs was conducted with different matrix permeability values. Figure 4 shows the transient behavior of different cases for the Madison area. Note that as the time increases, only the high-permeability cases show quick decline in flow rates. Also, there is a sharp decrease in flow rate as the permeability is decreased at higher values. For the lower range of permeabilities, the ahsolute value of the permeability begins to lose impact on the flow rate. Starting from a peameability of 10^{-12m3}, the flow rate appears to be completely dominated by fracture flow.

Scaling up

Finally, a series of numerical runs was conducted to observe the flow behavior for a scaled up version. For these geometrical scale up factor was chosen to be 100. Consequentely, length, thickness and width of the model were all multiplied by 100. Besides, the fracture width and the fracture spacing were also increased by a factor of 100. Also, the pressure values (at the boundary) were increased by a factor of 100. This approach would, therefore, correspond to the low pressure modeling approach [Bansal and lslam, 1994]. Figure 5 shows the field scale results for two different permeabilities of the matrix. Note that the time required to reach steady-state is ahout 10,000 times longer than that reported for the smaller scale. This shows the effectiveness of the scaling up approach. If the geometrical scaling factor is 100, the time scaling factor should be 10,000 (=100x100). Also, the order of magnitude of the flow rates shows that the field flow rate is 10^6 times higher than the laboratory scale flow rate. This is indeed commensurate with the scaling requierments, which dictate that the flow rate be scaled down by a factor of a^2 if the geometrical scaling factor is a.

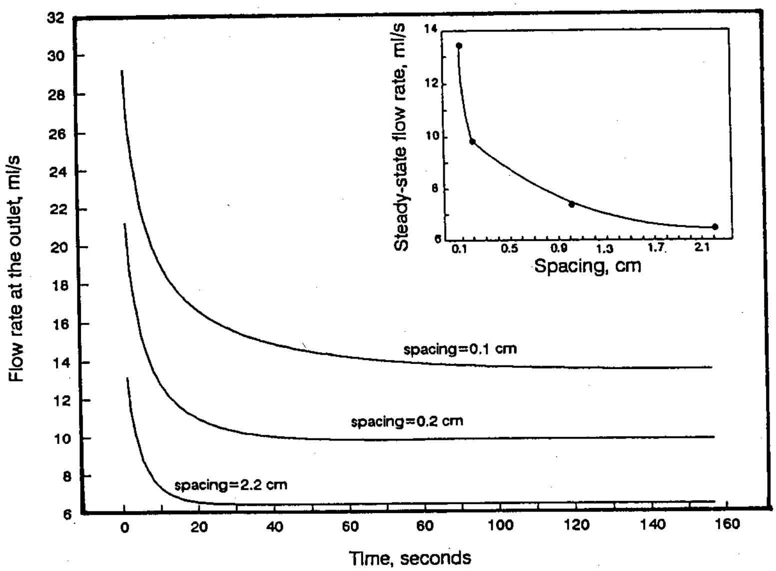

Figure 3. Effect of fracture spacing on flow rate

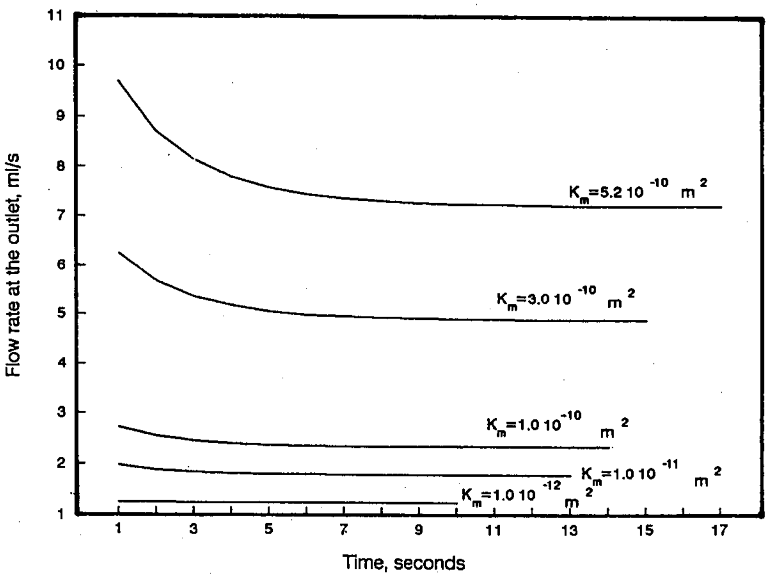

Figure 4. Effect of matrix permeability on flow rate

Another aspect revealed through this numerical excercise is the observation that by reducing the matrix permeability to $10^{-15} m^2$, one can reduce the effect of the matrix to storage alone. Figure 5 shows that for the lower permeahility value, the contribution to flow by the matrix is negligible (shown by the horizontal straight line) and the fracture flow accounts for the total fluid flux. This observation in effect eliminates the need of dual porosity model for formations with wide fractures and low-permeability matrix, for which the assumption of a homogeneous medium with certain anisotropy is applicable.

However, the dual porosity model collapses to the single-porosity case when the fracture width is selected in such a way that the fracture permeability equals the matrix permeability.

CONCLUSIONS

Experiments were conducted in scaled down models of three different formations in the Black Hills region, using both parallel plate analogy .and dual-porosity, dual-permeability approach. Numerical simulation was conducted for modeling fluid flow in a parallel plate model with flow through fractures only. For this case, a single-porosity model with appropriate anisotropy and equivalent permeability was found to be adequate. For the dual-porosity, dual-permeability system, the agreement between experimental and numerical results wa.s excellent. Parametric studies revealed that both fracture width and fracture spacing play an important role in determining unsteady-state as well as steady-state behavior. However, the most important region over which these two factors are important are lower values of spacing and fracture width. Matrix permeability, on the other hand, appears to be important only when its values are relatively high. At lower values of the matrix permeability, the flow rate was dominated only by fractures. Finally, scaling up was considered by modeling a prototype scaled up with a geometrical scaling factor of 100. It was found that the low-pressure models are adequate for modeling fracture flow through porous media.

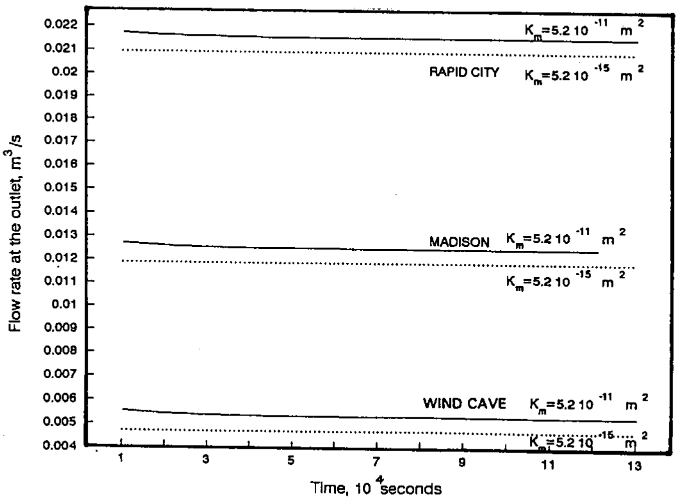

Figure 5. Field scale numerical results for different study areas

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Advantages of Air-Foam Drilling Methods for Construction of Water Wells in Eastern Abu Dhabi Emirate, UAE

Hassan Omer and Gerald Winter

ADVANTAGES OF AIR-FOAM DRILLING METHODS FOR CONSTRUCTION OF WATER WELLS IN EASTERN ABU DHABI EMIRATE, UAE

Hassan Omer and Gerald Winter
National Drilling Company
Al Ain, United Arab Emirates

ABSTRACT

The Ground-Water Research Project, a cooperative program between the National Drilling Company of Abu Dhabi and the United States Geological Survey, conducted test drilling to target semiconsolidated and consolidated-rock formations with a potential for high yield from secondary fracture permeability. The Project used the air-foam method to drill about 15,000 meters and construct 58 large-diameter wells between May 1995 and June 1996 near Al Ain in the Eastern Region of Abu Dhabi Emirate. The air-foam method utilizes compressed air and a biodegradable surfactant foam similar to detergent, in combination with injected water, to lift cuttings from the borehole between the drill stem and the borehole wall. The air-foam method is effective when drilling in consolidated formations, but may be less efficient than other methods when drilling in loose formations that are prone to caving. The air-foam method proved to be particularly effective for drilling boreholes in consolidated formations consisting of interbedded limestone, siltstone, and shale. The principal advantages of the air-foam method included: (1) a minimum of equipment; (2) high drilling penetration rate; (3) lithologic samples that are representative of the formations penetrated; (4) direct measurement of relative formation yield and specific conductance during drilling; (5) minimized need for geophysical logging to determine the lithology, permeability, and water quality of the aquifer; and (6) a minimum of well-development time because drilling fluid does not intrude the formation. The main disadvantage of the air-foam drilling method was the tendency to wash out zones composed of crumbling shale or swelling clay, which often needed to be cased off in order to continue drilling.

Keywords: Abu Dhabi Emirate, wells, drilling, air-foam method

INTRODUCTION

The Eastern Region of Abu Dhabi Emirate (fig. 1) is underlain by semiconsolidated alluvium and consolidated rocks including limestone, siltstone, and claystone. These formations represent Cretaceous-to-Quaternary age sediments about 1,300 feet (400 meters) thick that are overlain by a relatively thin layer of unconsolidated eolian sand of Holocene age. Because these formations are adjacent to the Oman Mountains, they receive runoff from mountain streams and, hence, comprise the primary fresh water-bearing aquifers in the emirate. In 1988, the National Drilling Company of Abu Dhabi and the United States Geological Survey began a comprehensive Ground Water Research Project (GWRP) to assess the ground-water resources of Abu Dhabi Emirate. Between October 1988 and March 1995, 124 wells were drilled in the Eastern Region and 43 wells

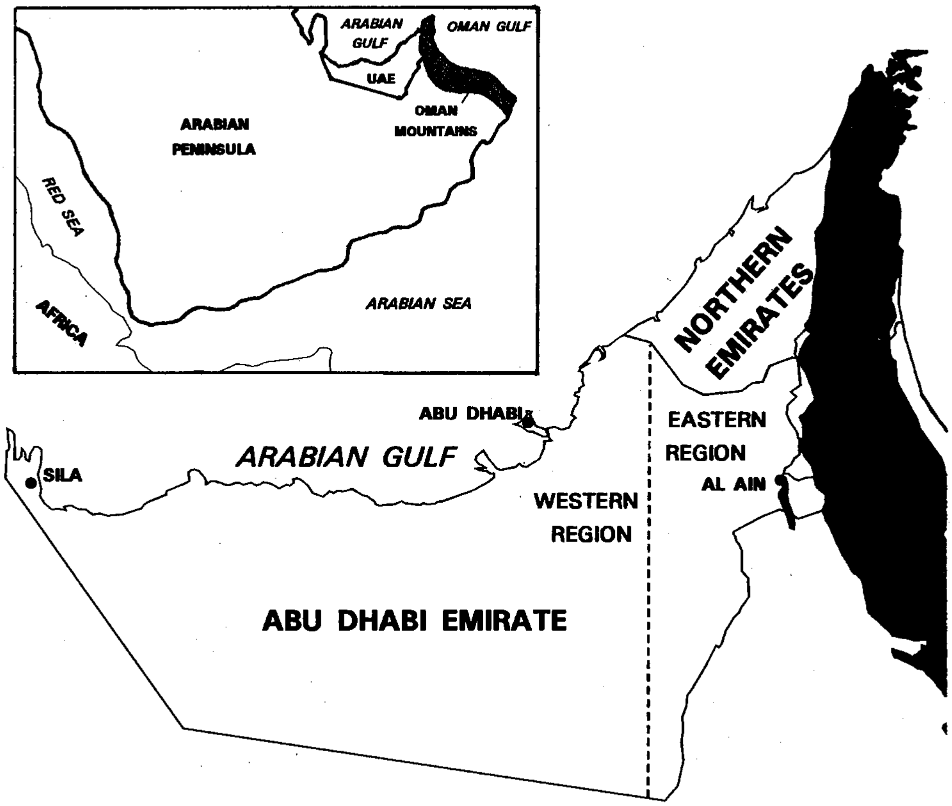

Figure 1. Eastern and Western Regions of Abu Dhabi Emirate.

were drilled in the Western Region using the mud-rotary method (fig. 2). The mudrotary drilling method proved effective for well construction; however, in 1995, the Project switched to the more efficient airfoam rotary drilling method utilized widely by water-well contractors in the emirate. Between May 1995 and June 1996, the air-foam method was used to drill 15,000 meters and construct 58 water wells in the semiconsolidated and consolidated formations of the Eastern Region to assess their potential for high yield from secondary fracture permeability. This report documents some of the successes and pitfalls of this changeover.

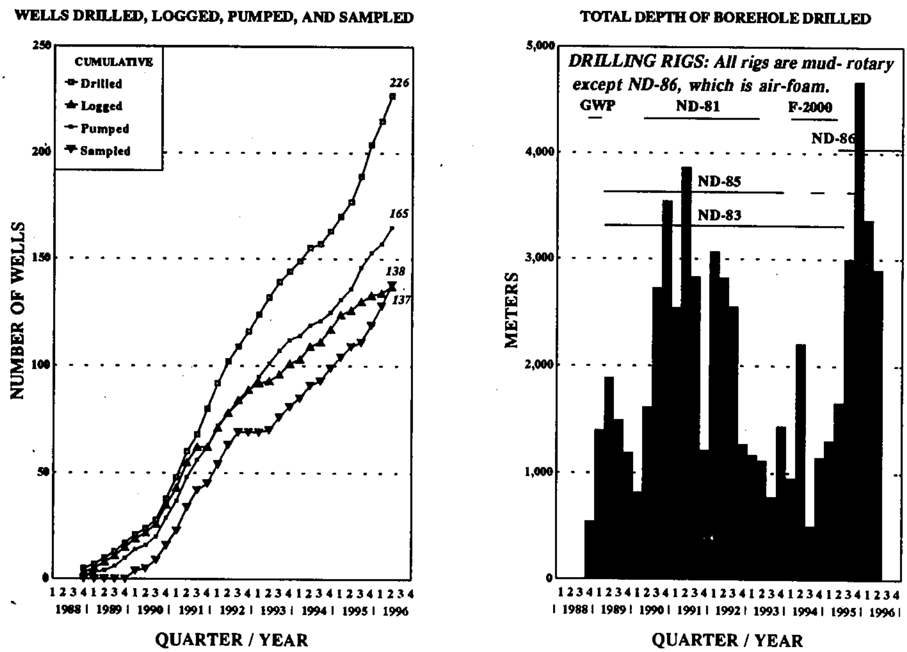

Figure 2. Progress of the GWRP test-drilling program, 1988-96.

AIR-FOAM ROTARY DRILLING

The air-foam rotary drilling rig is similar in appearance to a mud-rotary rig. The rig used by the GWRP is a Drilltech S40K3W truck-mounted unit (fig. 3) equipped with a large air compressor. The rig is also equipped with a small mud pump instead of the standard mud pump that is usually used for conventional mud-rotary systems. The unit has a depth capability of about 2,300 feet (700 meters) using 4.5-inch (6.35-centimeter) drilling rods. The rig has a top-head drive power swivel instead of a rotary table and kelly seen on conventional mud-rotary rigs. It utilizes a derrick and hoist and a pulldown system rated at 50,000 pounds (23,000 kilograms). The air compressor is rated at 350 pounds per square inch (25 kilograms per square centimeter) with an output of 1,000 cubic feet per minute (1,700 cubic meters per hour).

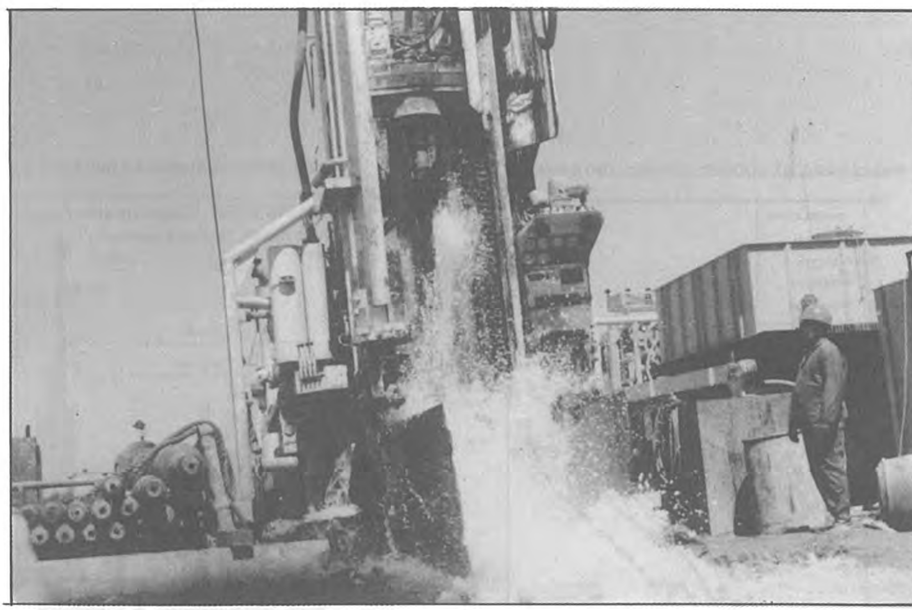

Figure 3. Air-foam rotary drilling rig, ND-86.

Detailed overviews of air-rotary drilling methods are presented by Campbell and Lehr (1973, p. 121-136), Driscoll (1986, p. 295-299), and Shuter and Teasdale (1989, p. 28-29). The air-foam drilling method utilizes compressed air to cool the drill bit and literally blow the drill cuttings out of the borehole. The "foam" is a mixture of water and detergent that increases the buoyancy of the cuttings, thereby reducing the psi required to lift them to land surface. The foam mixture is added to the hole through the drillstem at a rate of up to 25 gallons per minute (6 cubic meters per hour). If the formations penetrated by the borehole "make water", there may be several hundred gallons per minute of foamy water issuing from the borehole. For a typical 1,000-foot (300-meter) well in the Eastern Region, about 20 gallons (0.1 cubic meter) of surfactant may be used for the drilling process. The amount of surfactant is highly variable and depends largely on the salinity of the makeup water, formation water, and the absorptive capacity of clayey formations penetrated. Outflow from the borehole is gaged using a locally-fabricated V-notch weir (fig. 4).

Figure 4. V-notch weir used to gage outflow from the borehole during drilling.

DRILLING AND TESTING PROCEDURES

Drilling begins with a 22-inch (56-centimeter) borehole down to a semiconsolidated formation, usually about 50 feet deep. Then, 18.625-inch (50-centimeter) surface casing is installed and grouted. Intermediate 9.625-inch (24-centimeter) or 12.75-inch (32-centimeter) steel casing is inserted inside the 18.625-inch casing and grouted with one-half bag of cement or with 5 bags of dry bentonite to provide a temporary seal. Intermediate casing will be removed upon completion of exploratory drilling and logging. An exploratory 8.5-inch (22-centimeter) pilot hole is drilled with the operator noting changes of penetration rate and changes in the outflow gaged by the v-notch weir. The site hydrologist maintains a description of formations penetrated and measures the specific conductance of both the injected foam and the foamy water discharging from the borehole. Geophysical logs are conducted in certain key boreholes to define marker beds, estimate porosity, and profile the temperature and resistivity. The geophysical, drilling, lithologic, flow, and specific conductance logs are all used to determine hydrologic properties of formations and the quality of water contained. The information is used to design the completed well. The borehole is then reamed with a 17.5-inch (44-centimeter) bit to the desired depth and well casing and screens are installed. The screens are usually gravel packed and the annular space between the 22-inch (56-centimeter) and the 17.5-inch casings is filled with cement. The well is developed for a short time by surging with air. After the well is developed, a pump is installed and the yield of the well is tested for 5 hours. A plot of drawdown versus time is used to estimate transmissivity of the aquifer. If no problems are encountered, it usually takes about 7 days to set up, drill, construct, and test a 1,000-foot (300-meter) deep well.

The efficiencies of the mud-rotary and air-foam drilling methods are compared in.table 1. The GWRP rated the air-foam drilling method to be superior to mud-rotary in eleven of the thirteen categories listed.

Table 1. Comparison of mud-rotary and air-foam drilling methods in the Eastern Region of Abu Dhabi Emirate

Evaluation criteria	Mud-rotary method	Air-foam method
Drilling rate in unconsolidated sand and gravel	excellent	poor
Drilling rate in swelling clay	fair	poor
Drilling rate semiconsolidated fms.	good	excellent
Invasion of aquifer by drilling fluid poor	excellent	
Retrieval of cuttings	poor	excellent
Condition of borehole wall	poor	excellent
Well efficiency	fair	good
Circulation time	slow	fast
Life of drill bit (feet)	4,000	7,000
Identification of yielding fm.	poor	excellent
Ability to estimate salinity of formation water during drilling poor	excellent	
Penetration rate good	excellent	
Well development time poor	excellent	

Advantages

The air-foam drilling method has advantages over the conventional mud-rotary method for drilling applications in the Eastern Region of Abu Dhabi Emirate in that it is cleaner, faster, requires less equipment, and is more economical. Cuttings come out of the borehole clean. That is, they are not contaminated with drilling mud and are easier to identify, which facilitates compilation of a lithologic log from the drill cuttings. It is also easier to develop the well because there is no "mud cake" sealing the permeable formations. Perhaps the greatest advantage is the ability to log formation water salinity and potential yield during the drilling process (Table 2).

Table 2. Log of flow rate, fluid specific conductance, and lithology compiled during drilling by the air-foam method
(Multiply feet by 3.28 to obtain meters; multiply gallons per minute (gal/min) by 0.227 to obtain cubic meters per hour; µS/cm, microSiemens per centimeter)

Depth (feet)	V-notch flow rate (gal/min)	Specific conductance (µS/cm)	Lithology
300	308	3,400	limestone
320	350	3,800	limestone
330	630	5,230	limestone
350	700	5,180	silty limestone
450	700	4,980	shale

The well was cased to 206 feet and screen installed between 206 and 371 feet. A pumping test was conducted at a rate of 580 gal/min for 5 hours. Specific conductance at end of testing was 5,530 µS/cm.

The circulation time from the bottom to top of the borehole is very fast using air-foam. For example, experimental tests indicated that travel time from the bottom of a 1,000-foot, 8.5inch borehole, is about 20 seconds, and for a 17.5-inch borehole, about 100 seconds. For conventional mud-rotary drilling, the circulation time from such a depth may vary from about 10 minutes to 30 minutes, depending upon mud pump volume and borehole diameter. Equipment needs are less because a mud pit, shale shaker, desander, and related equipment for mud-rotary drilling are not used. The air-foam method proved more economical from the standpoint that drilling time was reduced, mud engineering was not needed, well-development time was reduced, and geophysical logging was minimized.

Disadvantages

Test drilling with the air-foam in the Eastern Region of Abu Dhabi Emirate has a few drawbacks. In some cases, where unconsolidated formations were encountered, they would tend to "wash out" leaving a cavity that threatened the stability of the drilling rig. In other cases, while drilling in fractured or cavernous limestone, circulation would be lost, whereby there were no cuttings returned to the surface., In this case, sometimes the borehole was drilled "blind" with the consequence that collapse might occur above the drill bit. Another major problem occurred while drilling through shale, which tended to swell or ravel above the drill bit, resulting in precarious withdrawal of the drill string. When these conditions were encountered, the troublesome section was usually cased off. However, in some cases, the drilling fluid was switched from airfoam to bentonite-mud. Unfortunately, the small mud pump supplied with the rig is inadequate for deep mud drilling.

RESULTS

The results of the GWRP drilling program over one year using both the air-foam and mud-rotary drilling methods are compared in table 3. There was approximately a threefold increase in footage drilled and number of wells completed when the air-foam method was used. This, along with more than a 50-percent reduction in drilling time per well and a 20-percent annual cost reduction, provides strong support for continued exploration drilling in the Eastern Region of Abu Dhabi Emirate using the air-foam rotary drilling method.

Table 3. Achievements during one year of operation using the air-foam and mud-rotary drilling methods in the Eastern Region of Abu Dhabi Emirate (multiply feet by 3.28 to obtain meters)

	Mud-rotary method	Air-foam method
Footage drilled (excluding reaming)	15,637	46,115
Number of wells completed	18	45
Average depth of borehole, in feet	870	1,000
Cost, in millions of dollars	1.4	
Average time per well, in days	20	8

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WATER SUPPLY AUGMENTATION THROUGH ARTIFICIAL GROUNDWATER RECHARGE TECHNIQUES

Mohamed J. Abdulrazzak
United Nations
Economic and Social Commission for Western Asia
Amman, Jordan

ABSTRACT

Increasing demand for water, in conjunction with diminishing supplies due largely to insufficient natural resources, make it necessary for the countries of the Arabian Peninsula to implement both demand and supply management measures. The most feasible options are water conservation and augmentation of supplies through increased water reuse and artificial groundwater recharge. Past experiences indicate that when properly operated and maintained, recharge dams have achieved the required objectives. However, other recharge methods, especially spreading basins and recharge wells, can become an effective means in restoring aquifer equilibrium and for storing excess flood water, properly treated waste water or imported water to be used during times of need. The building of strategic water reserves is of particular importance in the and countries of the Arabian Peninsula.

Artificial recharge schemes must be considered an integral part of any water resource management scheme, and an important component for preserving the national water supplies. Successful implementation of supply augmentation techniques requires careful preliminary investigations of natural field conditions, in addition to the assessment of financial, economic and cultural aspects. By giving due consideration to the use of proven artificial recharge techniques, countries of the Arabian Peninsula can improve water resource management through optimal utilization of runoff, reclaimed wastewater, excess desalination, or imported water. In addition, knowledge and experiences associated with implementing artificial recharge schemes in any country of the region should be invaluable to other countries in the region due to their similar hydrological, geological, climatic and social characteristics.

Keywords: Artificial Recharge, Infiltration, Supply Augmentation, Recharge Techniques

INTRODUCTION

Water shortages in arid and semi-arid regions of the world can constitute a major limiting factor to sound socio-economic development. The availability of water in the countries of the Arabian Peninsula, characterized by extremely and conditions, varies tremendously depending on a number of factors including geographical location, geology, topography, and predisposing atmospheric conditions. In countries where groundwater in shallow and deep formations is the only reliable source of fresh water, development of an aquifer without proper management may lead to overdraft. Currently, water demands for domestic, industrial and agricultural purposes are being met mainly through exploitation of deep and shallow aquifers, desalinization, and to a limited extent the use of treated effluent. Extensive use of groundwater where withdrawal in excess of the natural recharge have resulted in both a progressive decline in the piezometric head and a lowering of the water table. This, in turn, creates potentially critical conditions which endanger the life and usefulness of the underground aquifers which are the only renewable source of water.

Long term development and management of groundwater, especially in the alluvial and other shallow aquifers, depends on the establishment of a balance between recharge and water withdrawal. To accomplish this, the recharge components must be carefully assessed and enhanced through augmentation by artificial recharge measures. In addition, the understanding of recharge mechanisms contributes significantly towards the improved recharge facility design, operation and maintenance. However, evaluation of the recharge process is considerably complex owing to the high degree of variability in geological, topographic and hydrological conditions. This variability may be due in part to the transient nature of the hydrodynamic flow processes in both the surface and subsurface soil profile, as well as soil heterogeneity. In addition, artificial recharge is also site specific and subject to human induced factors.

Management of natural groundwater recharge and enhancement of magnitude by artificial means can be of major benefit in increasing water supply availability for all countries of the region. Increases in the volume of groundwater recharge from surface runoff, especially for the countries of Saudi Arabia, Yemen, U.A.E., and Oman, can provide additional water to be used in time of need. The large volume of surface runoff is sometimes lost to the sea from coastal drainage basins and evaporation from inland drainage basins can be utilized for recharge purposes. The ratio of estimated flood volume to runoff being utilized ranges from high in Saudi Arabia (900/2230 mcm) to low in Qatar (0.25/1.35 mcm). Distribution is estimated at 900/2230 mcm in Saudi Arabia, 475/2000 mcm in Yemen, 275/918 mcm in Oman, 75/125 mcm in U.A.E, and 0.25/1055 mcm in Qatar. Enhancement of the recharge process can increase efficient utilization of available runoff. Only a small amount of treated waste water, estimated at 494 mcm, is being used in all of the countries of the Arabian Peninsula. The volume of reuse is very small compared to domestic water demand, which was estimated at 2727 mcm in 1990. The greater portion of treated waste water can be used to recharge aquifers.

Increases of aquifer recharge from runoff, excess desalination, treated effluent, and water imported from neighboring countries can provide strategic reserves of potable water. The building of such reserves presents a standby source that can be used under emergency conditions. Such schemes in different parts of the world indicate that with appropriate dam design and operation, or recharging wells and pits, most of the volume of water stored can usually be recovered at the time of need.

In this paper natural and artificial recharge processes are addressed in order to highlight their importance in achieving efficient management of groundwater resources. The discussion of natural recharge flow mechanisms and the influencing factors can contribute to better selection and implementation of artificial recharge schemes such as dams, pits, and spreading basins. The techniques of artificial recharge, especially those that are suitable to conditions in the Arabian Peninsula, are presented. Artificial recharge facilities currently existing in the countries of the Arabian Peninsula, as well as their performance, are discussed in order for others to draw on their experiences.

BACKGROUND

During the last decade, researchers and professionals have addressed the infiltration recharge process in and regions through a variety of means including simplified analytical solutions, isotope analysis, field studies, water balance and empirical approaches, and numerical methods. Some of those approaches have been used to circumvent the complexity of unsteady multidimensional flow and complicated boundary conditions

The infiltration-recharge process was addressed by several researchers through analytical and numerical approaches (Abdulrazzak & Morel-Seytoux, 1983; Besbes et al., 1978; Flug et al., 1980; Freyberg, 1983; Morel-Seytoux et al., 1990; Moench & Kisiel, 1970; Parissopoulos & Wheater, 1992 a & b; and Guzman et al., 1989). Field investigations were carried out by Sophocleous & Perry (1985), Steenhuis et al. (1985), Stephen & Knowlton (1986) and Crerar et al. (1988), Abdulrazzak et al. (1991). Isotope studies of the infiltration-recharge process were made by Foster et al. (1982), Sharma (1988) and MacLaren (1978). Abstraction from ephemeral streams was addressed by Sharp & Saxton (1962), Jordan (1977), Matlock (1965), Lane et al. (1971), Lane (1 983) and Walters (1989), Abdulrazzak et al. (1989), Sorman and Abdulrazzak (1993), and Abdulrazzak (1995). Some of those studies were supported with experimental data, and a few with field investigations.

Artificial recharge through the use of injection wells, infiltration basins, and dry river channels, has been successfully practised in many parts of the world. In the U.S.A. there are more than 30 known large scale recharging well projects that have been operational since 1968. In addition, there are a large number of surface basins and river channels utilized to recharge relatively shallow water tables. Most of these projects were implemented in sand and limestone formations for controlling salt water intrusion, building of groundwater reserves, storage of treated wastewater, and improvement of water quality. For example, a major recharge well facility is located in Orange County, California, for the purpose of combating salt water intrusion, with a line of 200 injection wells to inject $0.21m^3$ of reclaimed water per day. Recently, many projects have become operational in Florida and New Jersey for seasonal storage and recovery of treated drinking water (Pyne 1995). Most of these projects were implemented in limestone formations containing brackish water, and knowledge of these practices can be relevant to many countries located in the Gulf, for building strategic fresh groundwater reserves.

In other parts of the world such as Canada, the Netherlands and Australia, artificial recharge is being practised for management of water supplies and reducing salt water intrusion. There are major projects in Canada and the Netherlands where excess river flow is used to recharge shallow sandy aquifers for seasonal storage and recovery during times of need to meet municipal water requirements. In Australia recharge wells have also been used to store fresh surface water in brackish water aquifers to be recorded in dry periods for the purpose of supplementing irrigation demand. There are many other artificial recharge facilities using injection wells, that are either operational or in various stages of development, in Italy, Spain, India, Japan, Iran, Kuwait, and Qatar (Pyne 1994).

NATURAL RECHARGE PROCESS IN ARID REGIONS

Natural recharge in most regions of the Arabian Peninsula may occur through one or a combination of three processes: direct infiltration of rainfall over the watershed and outcrop areas of deep and shallow aquifers, infiltration of flood water, over-irrigation, or treated effluent flow through wadi beds of alluvial aquifers and leakage from one aquifer to another. The major portion of recharge usually occurs as a result of ephemeral flow in wadi channels which infiltrates into the underlying shallow alluvial aquifers. These wadi channels will often carry large volumes of water lasting a few hours, days, or exceptionally, weeks.

Flow Characteristics

The magnitude and frequency of recharge from ephemeral streams is dependent on the amount of water lost through infiltration into the wadi bed as the flood wave progresses in the downstream direction. Alluvial channels usually infiltrate large volumes of flood flow. The infiltrated volume initially satisfies the soil moisture deficit and evaporation requirements, and may eventually contribute towards recharging the alluvial aquifers (Abdulrazzak & Sorman, 1988), while the water supply lasts.

Groundwater recharge in most catchments of the Arabian Peninsula usually occurs from flood water loss through wadi channels and spreading basins. The transmitting zone between the surface and the underlying aquifer is the unsaturated soil profile. If water application (flood or diverted water) continues, the infiltrating wetting front propagates towards the water table, otherwise infiltration will cease and the previously infiltrated water will accumulate in the unsaturated zone and move downward under the influence of gravity. Following the discontinuation of water availability on the surface, evaporation begins to deplete soil moisture. Once the wetting front reaches the water table, recharge begins. The merger of the infiltrated front with the water table causes the flow to change to a lateral direction. Once a hydraulic connection is established by the advancing wetting front and the water table, recharge commences, and a mound starts to build up under the active channel width. The temporary hydraulic connection established between the ephemeral stream and the aquifer depends on flood duration, maximum stage, and depth to the water table.

In many instances, the presence of a surface crust layer in the wadi channel causes infiltration beneath the channel to occur under unsaturated flow conditions. The clogging layer, which usually consists of silt and loamy clay sediment, is deposited as flood flows recede. This layer controls the infiltration flux at the surface.

Influencing Factors

The magnitude of infiltration loss occurring through wadi channels, watersheds, and water bearing formation outcrops is influenced by various hydrological, hydraulic, and soil profile factors. Depending on the initial conditions, some of these factors become more dominant than others. The most important ones consist of rainfall-runoff and soil profile characteristics (intensity, duration, volume, peak, suspended load, channel geometry, surface crust layer, profile stratification, porosity, hydraulic conductivity, and initial moisture content, and depth to the water table, channel configuration and hydraulic aquifer parameters. Most of these parameters are characterized by large temporal and spatial variability.

Rainfall: The amount and distribution of rainfall indirectly influences the amount of channel runoff due to their direct relationship to the amount of runoff generated. The position of the storm center and its aerial coverage over the watershed determine the occurrence and magnitude of the runoff hydrograph and the consequent contribution to transmission loss (cumulative infiltration) (Abdulrazzak et al. 1991). Runoff generated in the upstream drainage basin usually has a better opportunity to infiltrate along the entire length of the wadi channel than runoff generated downstream close to the basin outlet, usually due to the presence of course bed material. The high intensity, short duration storms with small aerial coverage, which is typical of and regions, appear to occur in a random pattern resulting in the sporadic nature of this process.

Runoff: Surface runoff volume is greatly reduced by transmission loss during flood wave propagation in the downstream direction. The duration and magnitude of surface runoff has a predominant effect on water movement through the soil profile and its arrival at the water table. Large volumes of surface runoff during major floods inundate extensive contact areas, in terms of wadi cross-section, affording greater infiltration time. The magnitude of the stage hydrograph peak also effects the amount of loss occurring during flood events. The flood depth establishes the energy available to transfer water into the underlying alluvium. High flood depth with large volume can induce high infiltration rates, as well as large wetted area. In addition, turbulence associated with peak flow removes previously deposited sediment, thus enhancing the transmission loss.

It is expected that a large portion of the transmission loss (infiltration) occurs during the rising limb of the hydrograph, as opposed to the recession limb.

Due to low velocity flow during the recession period, a silt layer may be deposited which reduces infiltration. The width of the wetted area is a function of the flood volume, as well as the shape of the channel. For triangular or trapezoidal cross-sections, the width is linearly proportional to the stage area. For rectangular cross-sections, where the width is constant, the flood head allows a uniform head distribution and transmission loss (Abdulrazzak et al. 1991).

The frequency of flooding also influences the magnitude of loss. It is known that a dry channel will abstract larger volumes of water than a wet bed. Larger losses may occur as the length of the interstorm period increases.

Soil Characteristics: The amount of transmission loss (cumulative infiltration) is also dependent on the physical characteristics of wadi bed material and hydraulic properties of the soil profile and the underlying aquifer (soil moisture, hydraulic conductivity, porosity). The type of wadi bed material influences the infiltration rate across the soil surface. Low infiltration rate is usually associated with fine grain material, e.g. clay and silt. Gravel and sand allow high infiltration rates (high transmission losses) and lower field capacity. Bed material along the entire length of the channel usually consists of a mixture of unsorted gravel, sand, silt and clay. Coarse material is usually present in the upstream part of the drainage basin due to the erosive power of the flood flow. Consequently, higher losses may occur. However, the limited thickness of the alluvial material restricts the abstraction volume. In the downstream portions of the reach, silt and clay are deposited due to decreased flow. However, a wide wadi cross-section in the downstream area of the basin, together with low velocity flow, usually leads to a larger wetted area and longer contact time, resulting in larger volume of loss and consequent groundwater recharge.

The soil moisture conditions, porosity, and hydraulic conductivity of the alluvial profile influence the infiltration rate. Dry soil, in addition to high hydraulic conductivity values, may result in high abstraction volumes. High moisture content allows the flood wave to travel at a high velocity, resulting in less contribution to groundwater recharge.

A study of the wadi alluvial indicates that soil heterogeneity of coarse material with high porosity will permit faster movement of infiltrated water to the water table. The interstorm period in relation to soil moisture affects the amount of abstraction. The longer the period, the more likely the soil moisture will be depleted through evaporation. A study in the state of Arizona indicated that moisture in the top 1.5 meters of the soil evaporates as a result of capillary rise within a 15 day period after flood flow stopped.

Channel Characteristics: The hydraulic channel characteristics in terms of gradient, flow depth, roughness, meandering and vegetation, in relation to flow velocity, influences the amount of channel abstraction. Channel slope may govern the depth, duration and area of inundation. Steep slopes lead to high flow velocity and lower transmission loss rates. Coarse material tends to increase bed roughness suggesting decreased flow velocity. A braided channel will induce more loss than a single stream channel. Vegetation reduces the flow velocity and thus increases the inundated area and prolongs the period of flow. Also, vegetation depletes the soil moisture and increases the capacity of soil absorption, leading to an increase in infiltration rate. The factors addressed above usually act interdependently to form a dominant force in inducing wadi channel loss in alluvial channels.

The position of the water table will influence the rate and magnitude of infiltration (abstraction). A water table close to the land surface will inhibit transmission loss due to pore storage availability and resistance to flow as a result of groundwater mound build up. Theoretically, the infiltration rate decreases as the mound builds up to the soil surface. For a deep water table, the infiltration rate is initially high and may reach a constant value equal to the hydraulic conductivity. A high value of hydraulic conductivity will result in advancement of the wetting front to greater depths. The availability of pore space depends on the thickness of the alluvium profile. Greater depth will have larger storage space and thus a high transmission loss.

Aquifer parameters of storativity, transmissivity and thickness represent the mechanisms controlling the dispersal of infiltrated water both laterally and longitudinally. Aquifers with high values of specific yield and hydraulic conductivity can store significant amounts of water, as well as disposal of water in different directions. Aquifer parameters influence the growth of the groundwater mound underneath the recharge channel (Abdulrazzak et al. 1991). Thus, many surface and subsurface factors, including the unsaturated and saturated soil profiles, have influence on infiltration, percolation, and recharge processes Understanding the interdependency and influence of these factors will be beneficial in the design, implementation and operation of artificial recharge facilities. With regard to equations governing the movement of water across the ground surface, soil profile and build up of groundwater mount and its dispersion, interested readers may refer to the following sources: (Abdulrazzak et al. 1991, Morel-Seytoux and Miracapello 1988, Abdulrazzak and Morel-Seytoux 1983, Morel-Seytoux 1985, Walter 1990, Sorman and Abdulrazzak 1993, Parissopoulos and Wheater 1990, 1991, 1992 a & b).

ARTIFICIAL RECHARGE

Benefits of Recharge

Artificial recharge is aimed at augmenting the movement of water to the underlying aquifer by some method of construction: surface spreading basins, injection wells, or artificially modifying natural channel conditions through recharge dams and dikes. These techniques have been practised to reduce, stop or even reverse groundwater level decline, afford protection against salt water intrusion, and used for storage of water from rivers, floods, and reclaimed waste water for future uses (Helweg 1985, Morel-Seytoux 1985, Pyne 1995).

The benefits of artificial recharge of groundwater systems are numerous. The aquifer can be used for seasonal long term and emergency storage. Recovery of stored water can contribute to deferring expansion of water facilities, or to their downsizing with substantial cost savings. The formations in which water is stored may have confined, semi-confined or unconfined characteristics and varying rock composition. Seasonal storage may be practised to take advantage of the availability of excess water during the wet season. Such practices may be beneficial for the storage of flood water occurring over a short period in many parts of the Arabian Peninsula. Long term storage can be utilized in situations where desalination capacity is in excess of water demand. Emergency storage is of significant importance in building up strategic reserves of groundwater to meet demand when primary sources of water are unavailable, either as a result of contamination, warfare, or natural disasters. The availability of groundwater reserves represents a strategic option that needs to be implemented for many of the GCC countries because of the increased rate of groundwater depletion and interruption of desalination services due to the possibility of facility breakdowns or contamination such as oil spills. Such reserves will also prove valuable in the event of unforeseen disasters or sabotage of facilities.

Other advantages of artificial recharge schemes include the restoration of groundwater level, reduction of subsidies, land subsidences, and water quality improvement (Pyne 1995). The rate of groundwater mining can be reduced by increasing the rate of recharge, possibly reversing the condition using high rates of augmentation. Increasing pumpage for confined aquifers located near the surface usually results in land subsidence. Remedial solutions may lie in increasing the magnitude of recharge in order to increase pressure. Artificial recharge can contribute to water quality improvement through the reduction of concentration of DBPs such as trihalomehines [THMS] and haloacetic acid [HAAs], as well as their formation potential (Pyne 1995).

In addition, other improvements in water quality may include pH stabilization and iron, manganese, hydrogen sulfate, nutrients and coliform reduction (Pyne 1995). Storage of agricultural runoff can reduce nitrogen concentrations through bacterial denitrification. In addition, storing of recharged water, especially from desalinated sources, in limestone formations helps stabilize aggressive water.

Artificial recharge is considered one of the effective means to combat salt water intrusion along coastal zones. This phenomenon is being experienced in many of the GCC countries where excessive pumpage is in excess of natural recharge. Withdrawal from alluvial and limestone aquifers is accelerating the advancement of the salt water front. Flood water, prior to draining into the coastal zone on both the eastern and western sides of the Arabian Peninsula, as well as reclaimed waste water, can be used to build up a groundwater barrier. The same methods can also be used to control the movement of contaminant plumes.

The other important aspect of artificial recharge is the storage of reclaimed waste water. High quality treated water may be stored seasonally, to be recovered later for irrigation and industrial uses. The availability of treated waste water which is being disposed of along coastal zones or into wadi channels, in most of the countries of the Peninsula, can be put to beneficial use through recharging the alluvial aquifers. However, consideration must be given to the quality of treated effluent in order to avoid groundwater pollution, thereby reducing water supply. The treated effluent must meet potable water quality standards. Recharge with treated effluent may entail further treatment following conventional secondary treatment, to address health concerns with regard to stable organisms, heavy metals, and the presence of pathogenic organisms.

Though the advent of artificial recharge may seem to have many benefits, problems still may be encountered at some locations. Land to construct recharge facilities may not be available or may be too expensive to acquire. Artificial recharge may increase the danger of aquifer contamination, especially when the source is reclaimed effluent that fails to meet potable quality standards. The allocation of artificially recharged groundwater with regard to water rights and institutions to manage the aquifers may lead to long and costly litigation (Helweg 1985).

METHODOLOGY

A variety of techniques have been employed to artificially recharge the groundwater system. The methodology involves direct surface (water spreading), direct subsurface (subsurface injection) and indirect (induced infiltration from surface water) applications of water to enhance its movement or transfer to the underlying formations. The direct surface technique involves mainly recharge basin and stream channel modification, while direct subsurface methods employ the use of pits, shafts and wells. Indirect techniques involve the process of induced infiltration from surface water sources, as well as aquifer modification. The selection of a given technique depends on geological, topographical, hydrological, legal and financial conditions.

Spreading Basins: Direct surface techniques are among the oldest and simplest methods, and are widely used for enhancing the infiltration process across the land surface, as well as increasing percolation through the soil profile to the water table. Spreading basins allow efficient use of space and require only simple maintenance. Basin geometry is flexible, allowing construction to be modified according to the terrain. The use of multiple spreading recharge basins is advantageous as it allows longer water detention time, removal of sediment from the water at the first basin, and interchanging of basins to permit periodic maintenance (scraping and dishing). Spreading basins can be located along stream channels or cascading mountain slopes with water diverted from river flow, wadi floods and mountain runoff.

Spreading basins are being utilized along wadi channels in many parts of the Arabian Peninsula. Besides spreading basins, mountain terrace systems, which can be considered as multiple spreading basins, are used in Yemen, Saudi Arabia and Oman. The basins were intentionally constructed for cultivation purposes, but also serve to provide recharge to the usually shallow water table under wadi channels. The magnitude of recharge depends on the frequency of flooding within the basin, as well as the soil profile. Other spreading techniques may include flooding, ditches and furrows, dendritic and contour systems (Oaksford 1985) which are either constructed as independent facilities or in conjunction with the spreading basin. In general, spreading basin systems are known to work well in soils with high hydraulic conductivity and where adequate expanses of land are available. The infiltration capacity of spreading basins can be improved by soil treatment, vegetation and maintenance.

Recharge Dams and Dikes: The other direct surface method is stream channel modification which entails modification of the natural channel characteristics to increase infiltration volume and water storage by increasing the size of the contact area. Channel widening and dredging, as well as the construction of dikes and dams, increase infiltration. Dredging increases infiltration efficiency through the removal of the surface clay and silt retarding layer, and coincidentally increases the size of the stream bed exposed to water. Dikes and recharge dams seem to be better infiltration-recharge devices in comparison to other techniques, resulting water storage, increasing the water pressure head as well as increasing the size of the surface area, with a greater influence on static water head. The storage of flood water behind dams allows water to infiltrate over a large area. In addition, release of water also allows stream infiltration over long distances in the downstream direction. The construction of a series of small check dams also allows a larger area of channel to be covered with water, thus increasing infiltration time by reducing flow velocity. The efficiency of recharge dams depends on the operational procedures and maintenance used for the removal of accumulated silt and clay deposits. Recharge dams need to be constructed, where appropriate, in the upstream portions of the channel where the alluvial materials consists of coarse sand and gravel with will allow for greater infiltration rates. Channel material deposits become finer in a downstream direction. Channel modification usually involves relatively low construction and maintenance costs, with the exception of medium and large size dams.

The most widely used methods of channel modification used in the countries of the Arabian Peninsula are dams and dikes constructed across wadi channels. Recharge dams of various sizes have been built to enhance the recharge process in a large number of wadis in the region, especially in areas with seasonal rainfall and runoff. The main advantages of surface water application are: ease of maintenance, ability to store water, and greater detention time allowing increased infiltration.

Recharge wells: Direct subsurface recharge techniques consist of conveying or transferring water directly into the aquifer. The technique is used to overcome the presence of impervious stratum separating the source of recharge from the aquifer needing replenishment. Injection wells are the most widely used method of subsurface recharge. Construction of injection wells is similar to that for discharge wells, however emphasis is placed on the installation of screens and gravel packs for unconsolidated aquifer material. Injection well design depends on the objectives of the recharge scheme, the volume and quality of water to be injected, natural groundwater quality, and aquifer hydraulic characteristics (storitivity, transmissivity, gradient and thickness). Due consideration should be given to the problem of suspended solids, biological and chemical impurities, dissolved gas and water temperature, especially in less permeable aquifers (Oaksford 1985).

Recharge wells are not limited to replenishment of a single aquifer, and water does not necessarily have to come from a surface source. Several aquifers can be simultaneously recharged from a single or multi-injection well. The aquifer storage recovery system (ASR) relies on multi-purpose utilization of a well or series of wells to inject water during times when excess water is available, to be recovered during times of need. This technique has recently gained considerable attention because of its many benefits (Pyne 1995). Recharge wells have also been used to store excess water from rivers or floods, reclaimed waste water, and imported water, to be recovered later for the purpose of creating fresh-saltwater barriers in coastal aquifers. Such schemes provide better overall management of groundwater resources. Dual purpose wells are the most suited method for achieving recharge objectives, while controlling well plugging due to the presence of suspended solids in the recharge water (Pyne 1995). For further information on the technical and administrative aspects of the ASR system, please refer to Pyne's book listed in the references.

Limited recharge injection well schemes have been experimented with in Kuwait and Qatar to study the feasibility of building up strategic reserves. The sources of water for injection purposes were supposed to be excess desalinated water or imported water from neighboring countries.

Pits and Shafts: The other direct subsurface recharge technique makes use of pits, shafts, and natural openings. The process involves the digging or drilling of deep pits or shafts that penetrate the semi-pervious layer to convey water directly into the underlying water-bearing formations. The pits and shafts are filled with coarse material to facilitate rapid movement of the water into the aquifer. The shafts are deeper than the pits, and smaller in diameter (Oaksford 1985). However, they are susceptible to clogging by suspended solids or biological activities, and are difficult to maintain. Recharge pits were experimented with in Kuwait. In the countries of the Arabian Peninsula a large number of gravel pits and quarries are located alongside or within wadi channels, and these can be used for recharging purposes. Flood water can be diverted for such purposes. In addition, natural openings caused by fractures and limestone solution cavities can be used to recharge aquifers. Natural limestone cavities are numerous in the GCC countries of Saudi Arabia, Qatar and Kuwait, which can be utilized as recharge pits. In general, the main advantage of subsurface recharge is the use of excess water to recharge deep aquifers.

Recharge schemes may involve a combination of spreading basins with pits, shafts or wells. Spreading basins, in addition to storing water allocated for infiltration, can also convey water to pits, shafts or wells in order to disperse water rapidly into the permeable zone. Due to its flat topography, Qatar is using a recharge scheme consisting of spreading basins and wells to enhance the recharge process to the underlying limestone formations. The source of water is flood flow collected in a large number of depressions. The response of observation wells has documented the relative success of this recharge scheme.

Induced Recharge: Indirect recharge schemes involve lowering the water table through pumping in order to increase storage capacity. Water is pumped out and used during the summer months, creating more space for excess water in received in the winter months to be stored. This practice has been utilized in wadis Bishah and Turbah in Saudi Arabia, where the aquifer storage capacity is less than the available runoff (Abdulrazzak et al. 1991). Water is usually pumped for irrigation purposes prior to the flooding season to dewater the aquifer. During the set season, flood water can then contribute significant volumes to the aquifer.

Another situation deals with stream-aquifer interaction; the aquifer is pumped to induce recharge from hydraulically connected surface water bodies such as lakes or rivers. Another means of enhancing the recharge process is through the modification of aquifer systems through the construction of underground dams to increase aquifer storage capacity in areas behind the dam, and reduce the groundwater velocity. This technique is usually practised in aquifers with steep groundwater gradients. Underground water dams were built in wadi Turbah in Saudi Arabia to build and regulate groundwater storage for water supply purposes. The source is flood water. The advantages and disadvantages of different recharge methods are shown in Table (1).

ARTIFICIAL RECHARGE APPLICATION IN SELECTED ESCWA COUNTRIES

As the countries of the region begin to face serious water shortages, the need to implement programs emphasizing water resource management, including management of surface water, become increasingly critical. Some of the countries such as Saudi Arabia, Yemen, Oman and the United Arab Emirates initiated extensive number of programs to utilize the available surface runoff, and enhance the management of their limited water resources through building of recharge dams and spreading basins while others were experimenting with the feasibility of well recharging schemes.

Three types of flood runoff utilization techniques are currently being practised to augment groundwater supply through artificial means, in five of the Arabian Peninsula countries; Saudi Arabia, Yemen, Oman, United

Arab Emirates and Qatar. These management practices consist of storage facilities such as dams and dikes, water spreading, basin and depression lowlands with recharge wells which are being used in areas with adequate rainfall and runoff potential to recharge the shallow aquifers.

Recharge Dams: The main water management practice consists of storage facilities including the construction of dams of various sizes (E/ESCWA/NR 1993/19). Runoff is impounded behind these dams, thereby enhancing recharge to the underlying alluvial aquifers. Recharge to the alluvial aquifer takes place from within the dam reservoirs as well as through the downstream channels when water from the dam is released. In addition to enhancing the recharge process, the dams trap the majority of sediment load and reduce the magnitude of peak discharge, thereby reducing flood damage downstream. Most of the dams built in Saudi Arabia, the United Arab Emirates and Oman were built for the purposes of groundwater recharge, flood control, and in a few cases to provide water for irrigation or domestic purposes. The majority of dams built in Yemen were intended to divert flood water for irrigation and for groundwater recharge purposes. A few large dams in Saudi Arabia were constructed to serve a variety of purposes including irrigation, flood control and groundwater recharge. These dams have been built either at the head waters of catchments in the mountainous regions or in the downstream portions of catchments in Saudi Arabia, Yemen, the United Arab Emirates, and Oman.

Dams of various sizes were built to increase water conservation, provide flood protection and promote groundwater recharge, as shown in Table (2). The number of dams in constructed in all the countries of the Peninsula within the last ten years has reached more than 256, and at least 58 new dams are planned for the next decade. (E/ESCWA/NR 1995/19). Most of these darns have been built in Saudi Arabia, especially in the western and southwestern regions where relatively abundant runoff is available. Approximately 190 dams of various sizes have already been constructed in Saudi Arabia, and ten in Yemen, with a combined storage capacity of 475 and 72 mcm, respectively. Most of the dams in these two countries were constructed in mountainous regions because of the availability of runoff generated from the frequent occurrence of rainfall events, and high infiltration characteristics of the coarse wadi bed deposits. Fewer dams have been or are being constructed in the United Arab Emirates and Oman. In general, characteristics of dams built in the central, northern and northeastern part of the Peninsula include large reservoir areas, extensive length and limited height. They are usually of the earthfill type with large spillways. Those built in the western, southwestern and south-eastern parts of the Peninsula, especially in the mountainous region, are relatively small in terms of height

Table (1) Major Artificial Recharge Techniques (after Al-Heibe, 1993)

Method	Design and Management Factors	Advantages	Disadvantages
Spreading Basins	Frequency of flooding, drying, cleaning; pre-treatment of water; maximizing hydraulic loading, type, purpose, operational rules	Low construction cost, rapid implementation, low maintenance and repair costs, customary water rights.	Large land area required, soil clogging, algae blooms, insect breeding, less control of placement, land use conflicts, flood destruction.
Recharge Dams	Intermittent reservoir filling; surface treatment to remove silts and fines, operational role released, small surface area, large depth, outlet for sediment, type, construction.	Recharge to shallow aquifers, flood control, conjunctive use, continuous and high recharge volume, storage benefits.	Unreliability of annual refill, plant and equipment on standby in all years irrespective of expected flows, siltation, evaporation, contamination, high cost.
Pits and Shafts	Cleaning of pit base to maintain high infiltration rate; plant and equipment to maintain, standby, simple design.	Less land for spreading, large immediate storage capacity, low costs, easy access to aquifer.	Maintenance costs high, clogging, contamination, limited strata penetration.
Recharge Wells	Well design, power requirements, pumps, pipework, air release valves, flow meters, well development, injection-recovery efficiency, well layout.	Direct access to target aquifer, minimum system losses, minimum land requirements, range of depths.	Suspended solids, clogging, organic slime formation, potential of chemical precipitation, water right disputes.

Table (2) Numbers and Purposes of Dams Constructed in Some of the Countries of the Arabian Peninsula

Country	Recharge Dams	Flood Control/Irrigation	Planned	Storage Capacity at Completion in mcm
Saudi Arabia	120	70	9	0.01 - 325
Yemen	-	17	1	0.5 - 369
Oman	15	26*	14	0.01 - 12.5
U.A.E.	8	-	5	0.25 - 18.5
Total	141	103	39	

* Small retention dams

and storage capacity, and are usually constructed of concrete or rockfill. Due to flat topography and limited runoff in the remaining countries of Bahrain, Kuwait and Qatar, small diversion structures are used instead of dams to create detention basins (E/ESCWA/NR 1993/19).

Dams seem to achieve their intended purpose. Due to the natural coarse alluvial deposits in locations where dams are built across wadi beds, water impoundment and downstream water releases usually contribute significant amounts of water to the underlying aquifer. During and after flooding events observation wells located upstream and downstream of some dams in Saudi Arabia and the U.A.E have shown seasonal responses. Infiltration-recharge rates are usually more significant from downstream release than from the dam reservoir. Slow downstream releases offer a greater opportunity for infiltration through course wadi channel bed material. In addition, released water has less suspended material to hinder the infiltration process. In mountainous terrain, water stored behind dams moves rapidly into the underlying aquifer. The magnitude, however, is usually small due to the limited storage capacity of the aquifer, and the steep groundwater gradient that disperses water in a downstream direction. Similar situations have been experienced in Yemen, Oman and the United Arab Emirates.

Saudi Arabia: A study of selected dams in central Saudi Arabia (Al-Dalooj *et al.*, 1983) revealed that, in general, most of the dams served their intended purpose of recharging the alluvial aquifer. Downstream release and groundwater flow under the dams contributed to groundwater recharge, as reflected in downstream wells, and illustrated in Figure (1). Flood protection was provided for the rural communities downstream, and agricultural activities in the areas around the dams increased.

Recharge efficiency of two small dams located in the central part of Saudi Arabia was investigated by Al-Muttair *et al.* (1989) through field and theoretical analysis. This study concentrated on the evaluation of recharge magnitude from two dams, one under normal operation and storage conditions, and one with varying management options for silt removal and surface layer scratching. The dams studied were constructed of rockfill and concrete. Data on groundwater level, reservoir water level, climatic data and downstream releases were used to estimate the infiltration losses and resulting groundwater recharge. Results of reservoir water budgeting were checked against infiltration values and groundwater budgeting approaches. The study confirmed that significant volumes of water infiltrated through the dam reservoir even in the presence of silt and clay deposits, as shown in Figures (2 & 3). The efficiency of recharge from the two dams ranged from 68-94% while the evaporation losses ranged from 4-14%. However,

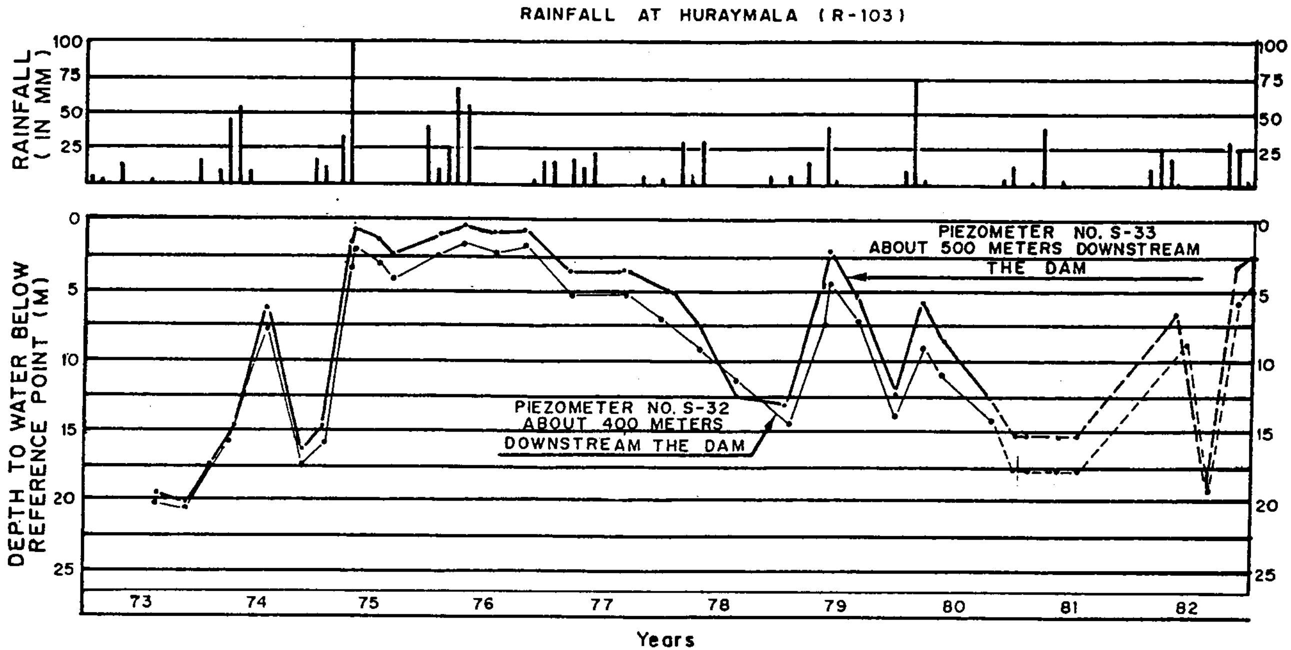


Figure (1) well hydrograph of Malham dam in the central region of Saudi Arabia (After Daloog 1982)

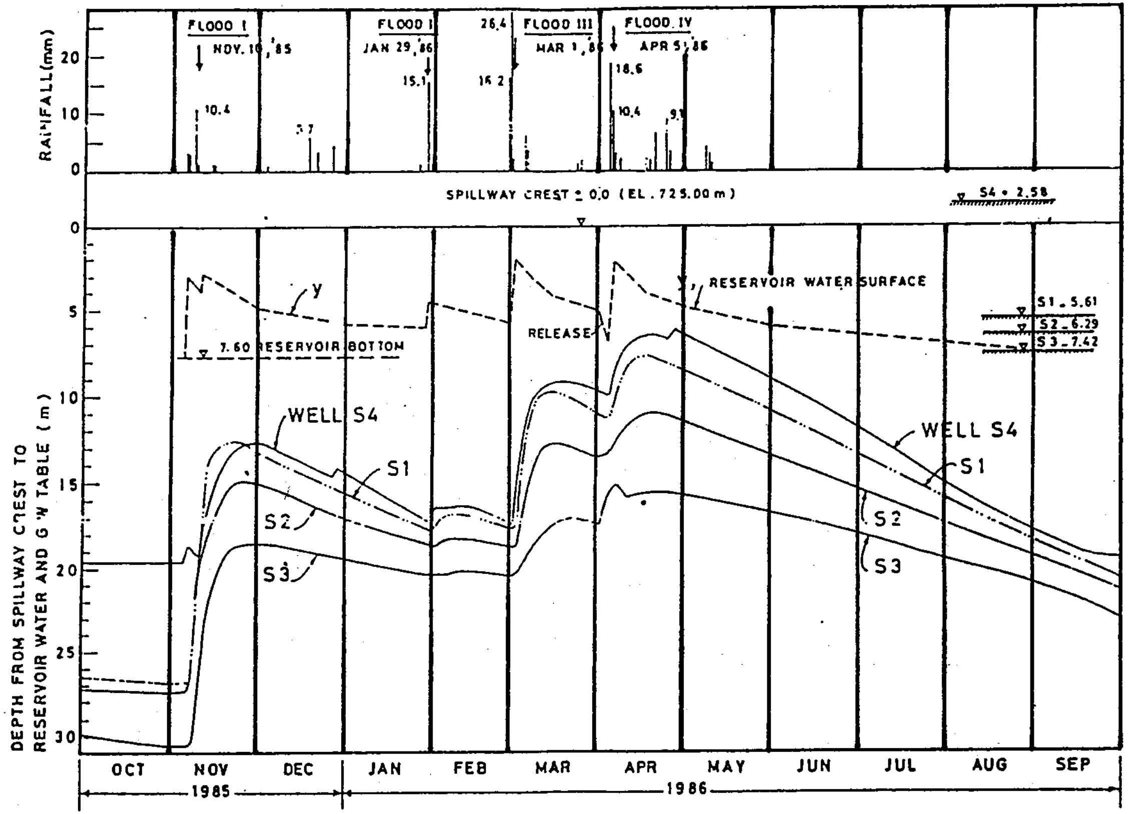


Figure (2) Weekly values of recharge volume, runoff value and rainfall depth in Al-Amalih dam in the central region of Saudi Arabia (After Al-Muttair, *et al.* 1989)

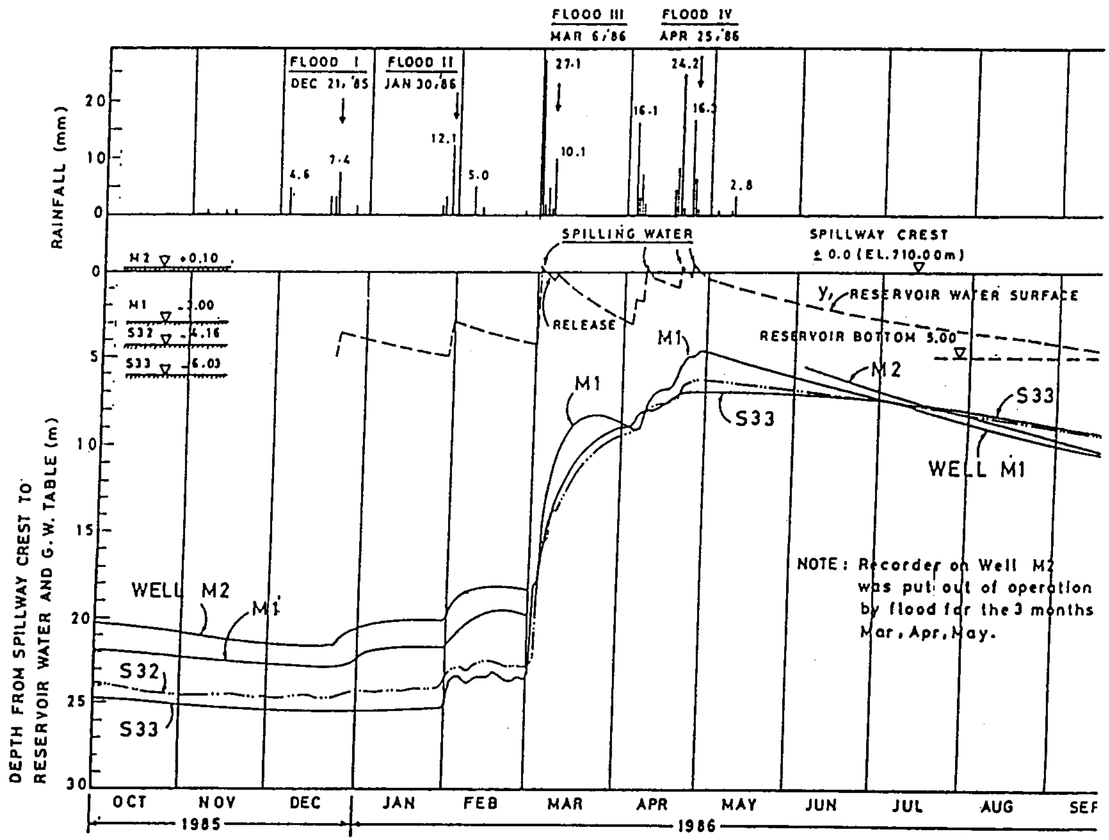


Figure (3) Weekly values of recharge volume, runoff value and rainfall depth in Malham dam in the central region of Saudi Arabia (After Al-Muttair, *et al.* 1989) evaporation losses increased to 60% during the summer season. Infiltration and recharge efficiency was shown to be dependent on the magnitude of runoff volume, silt and clay deposits, initial moisture and thickness of underlying alluvial deposits. Limited silt removal and layer scratching enhanced the infiltration process by 3 to 14%. Cost benefit analysis of various management options including no, or gradual downstream release of flow into the natural channel or into infiltration basins, and silt and surface layer scratching resulted in a ratio greater than three. The study concluded that dams in the central part of Saudi Arabia served their intended purposes of flood protection and enhancing the infiltration-recharge process to the underlying shallow alluvial aquifers. The study of Al Muttair et al. (1989) represents the most comprehensive evaluation of dam performance in the Peninsula.

Oman and United Arab Emirates: In the United Arab Emirates and Oman most of the dams were built in the lowlands achieved their objectives of groundwater recharge, flood protection to farmland and reduction of saltwater intrusion. The impoundment of water behind the Khod, Khilts and Quryat dams located in the coastal plain during flooding events from 19861988 (Al-Asam, 1990) resulted in groundwater rises of .3 to 2 meters. As expected, high rises were reported in the main wadi channel and decreases were reported in the flood plain. Salinity in some of the wells decreased from 25,000 to 10,000ppm and in others from 10,000 to 6,000 ppm. The contribution of surface runoff to groundwater recharge from some of the relatively large dams in the United Arab Emirates, such as those constructed on wadi Ham, is shown in Figure (4). The magnitude of recharge depends on the volume of runoff. Higher recharge magnitudes were shown to occur near the dam, as reflected by observation well response, as shown in Figure (4). In Oman, dam recharge schemes also included diversions to spread the flood water over a large area. No data are available for dams built in the remaining countries of the Peninsula, however, different degrees of effectiveness have been demonstrated in providing flood protection.

In some cases where dams have not served their intended purposes, problems were attributable to inadequate maintenance and operational procedures. There were also problems associated with high evaporation losses resulting from prolonged storage of water in the reservoir, high siltation rates with inadequate removal, and lack of proper operation and maintenance of controlled outlets. Infiltration rates from reservoirs became reduced with time as a result of progressive deposition of silt and clay. Siltation within reservoirs is a major problem in many parts of the Peninsula due to the high sediment concentration. Sparse vegetative cover in combination with steep slopes, exposed rocks and high intensity rainfall, results in high concentrations of silt and clay being carried along by flood waters. Lack of regular water release, especially during periods when the reservoir's water level is low, contribute significantly to water losses through evaporation. Dam efficiency is sometimes enhanced through silt removal from reservoir lakes and regulated downstream release of water, with the objective of contributing significant volumes of water towards recharging the underlying aquifers.

General rules governing the operation and maintenance of dams of various sizes are based on achieving optimum utilization and allocation of stored water for different purposes. Operational rules emphasize achieving direct and indirect benefits for users and repayment of dam costs. Dams built in different parts of the world, especially in regions where water is abundant, are designed to be cost-effective and financially viable while providing maximum benefit. This is usually possible due to a continuous supply of water through river flow. In the Arabian Peninsula, however, a continuous and dependable supply of surface water cannot be guaranteed due to the random nature of rainfall and runoff. Water stored behind dams cannot be considered a dependable source for supply and irrigation purposes, and most dams are therefore considered to be investment risks. They are built mainly to provide flood protection and enhance groundwater recharge, and may be expected to provide only limited sources of water for irrigation.

The operational guidelines being implemented for most of the dams already constructed do not stipulate the achievement of optimum utilization of stored water. Lack of uniform operational guidelines results in a number of difficulties with the operation of a given dam, with the use and distribution of water and with the inhabitants upstream and downstream of the dam. While most dams are equipped with spillways, water release usually occurs from flow over ungated spillway crests. Other dams have low-level regulatory valves which are sometimes used for water release. Sometimes water is stored behind a dam for long periods o time, and significant volumes are lost to evaporations and through infiltration. Evaporation results in substantial loss of water, especially for dams with large surface area reservoirs; the problem being intensified during the summer months. Release of water for recharge is usually not carried out according to well designed regulations. There may also be conflicts between upstream beneficiaries who want large volumes of water kept behind the dam to increase upstream recharge, while beneficiaries downstream request that water be released for agricultural and groundwater recharge purposes; such conflicts are particularly troublesome for small dams. Lack of gate maintenance sometimes hinders water release operations. The most efficient use of water for most of the regions of the Peninsula would be to release small amounts

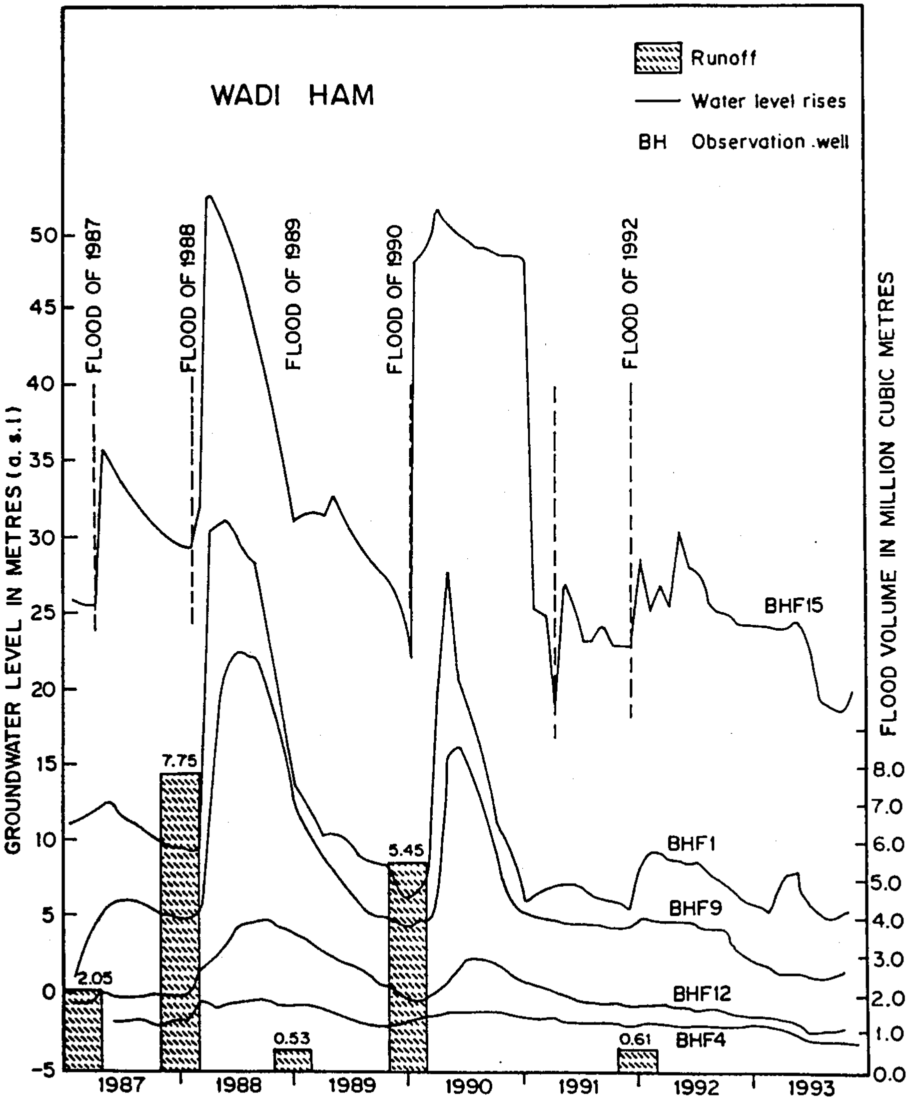


Figure (4 ') Runoff contribution to ground water recharge from Al-Ham dam in the United Arab Emirates (After Al-Asam 1994) over short periods of time to enhance infiltration.

Water Spreading Basins - Water spreading, known as flood irrigation or spate irrigation, is the simplest type of water harvesting, where cultivated areas lie within and immediately adjacent to an ephemeral stream or wadi. In many areas of the Arabian Peninsula, direct use of flood water for irrigation or groundwater recharge is small compared to the amount of available surface runoff. Spreading, which involves the use of small cultivated basins adjacent to the main wadi channel where flood water is diverted to meet crop water requirements has been practices in Saudi Arabia, Yemen, Oman, and United Arab Emirates. Flood irrigation within basins is still being widely practised in the downstream areas of major wadis in the southwestern region of Saudi Arabia, and in most regions of Yemen and Oman. Cultivation of the flood plain is carried out through construction of small basins that are prepared ahead of the rainy season along the main wadi course. They may extend laterally for many kilometers as far as the flat terrain allows. Sources of water include either direct rainfall or flood water diversion. An example of the typical spreading system used in Yemen is shown in Figure (5)

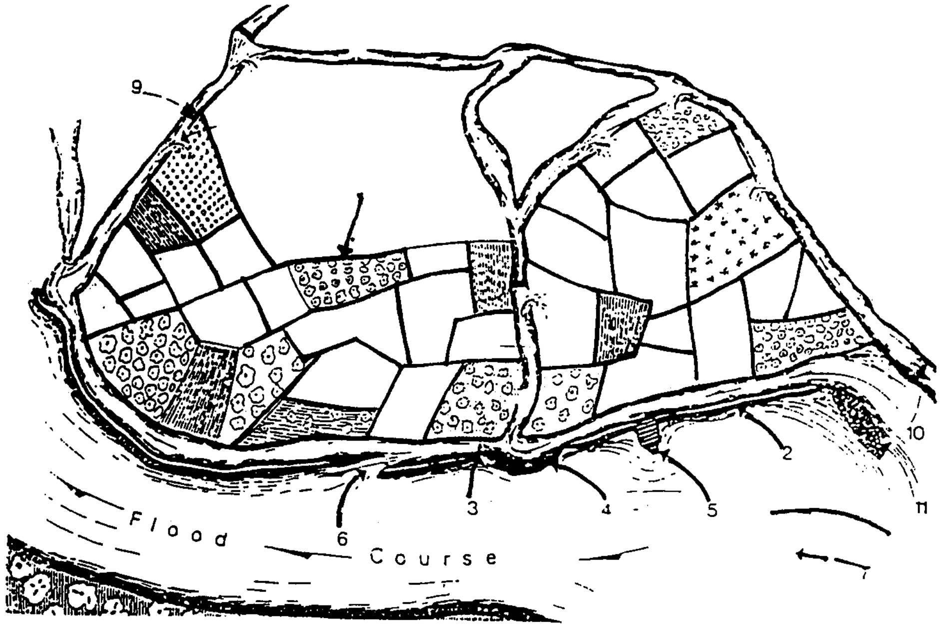
The main system of flood diversion is the construction of inexpensive earthen barrages, called weir terraces, built in succession across the wadi channel, or dike built into the tanque from the embankment. These structures raise the flood water level within the channel, causing it to collect in cultivated basins which are usually less than one meter high. They are generally constructed of sand and gravel. Diversion barrages are suited for narrow wadi channels in upstream catchments, while dikes are mainly used for wide wadi channels in the lower end of basins. Depending on the magnitude and duration of flood flow, the upper basins fill first, followed by those located laterally adjacent to the wadi, according to established allocation water rights. Subsequent downstream basins are filled in progression of the stream flow, and water is distributed according to local customs. More recently, series' of check dams have been used in conjunction with the diversion structures to increase the size of the irrigated area. This method is being used downstream of the wadi Jizan dam in Saudi Arabia. Just upstream there is a check dam conveyance channel that runs parallel to the wadi channel and distributes the flow laterally into adjacent spreading basins. Cultivated basins serve as a spreading ground to enhance the infiltration process and aid in groundwater recharge. Most basins are usually characterized by soil of reasonably high hydraulic conductivity, fertility and holding capacity. Barrages are frequently overtopped and in major floods they may be completely removed and the bed may scour. In extreme floods, diversion structures are usually breached, resulting in loss of irrigated area. Depending on the flood magnitude and duration, some of the diversion barriers and small dams may last throughout the flood season, or may require repair or replacement. Upstream structures are usually washed out or require repair due to high velocity flow and sediment load.

Recharge Wells: Major efforts in using artificial groundwater recharge methods to augment water supplies have focused on recharge dams in most countries of the Arabian Peninsula. However, in the past, Kuwait (1966) and more recently, Qatar (1994), have been experimenting with artificial recharge wells and pits. The anticipated water sources were excess desalinated water, flood water and imported water. The purpose was to build a strategic groundwater reserve to be used during shortages. Brief descriptions of these pilot projects follows.

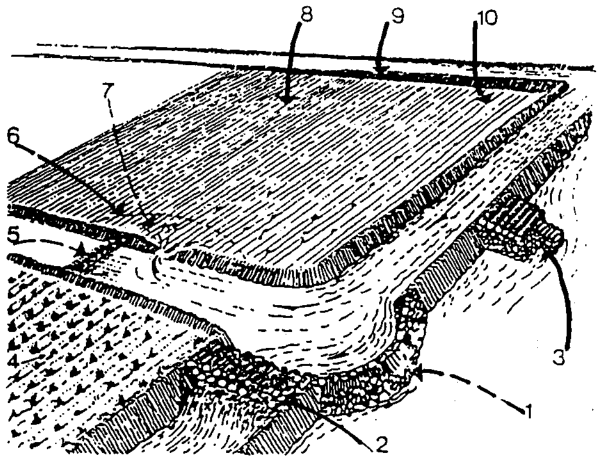
Kuwait: Excess desalinated water produced during the winter season in the past encouraged responsible groundwater authorities in Kuwait to evaluate artificial groundwater schemes. Preliminary hydrogeological investigation indicated that the sandstone formations of the Kuwait group at Rawadatain and the limestone Damman formations at Sulaibiya were potential recharge sites. The initial artificial recharge field investigations focused on the Rawadatain site because of the presence of a water supply well field consisting of 121 test holes and observation wells, as well as 26 production wells, completed in 1964 (MEW 1977). The Rawadatain aquifer represents the Dibdibba formation consisting of sandstone, conglomerate and siltstone. The first recharge experiment consisted of ten infiltration tests in two recharge pits, and two well injection tests during the period 1961-1964. The objectives of the tests were to examine aquifer behavior in order to evaluate formation storage capability and potential clogging.

Encouraging results were obtained from pits which showed high infiltration rates, leading subsequently to the construction of other pits in 1964, covering an area 870 ft long, 31 ft wide and 11 ft deep, which achieved 22000m^3/day. The source of water was runoff collected at Rawadatain which occurred in 1977 and resulted in water level rises of one meter, as shown in Figure (6), with a travel time of 80-90 hours (MEW 1977).

The well injection experiment at Rawadatain continued, and in 1972 two injection tests were carried out, later followed by a 27 day long injection test in 1973. The long test of 1973 provided results on recharge water level rise from 8.2 to 15.2 m, and its decay. Another injection test was made in 1977 to focus on water quality aspects. The outcome of various in ection tests favored the implementation of artificial injection-recovery schemes at the Kuwait group aquifers at Rawadatain. The scheme suggested the use of



1 AL-SAWM
2- SĀID AL-UBER
3- MA'QAM
4- GABW / JABW
5- KALB OR MASRAF
6 -MA'DBAL OR MANSAM
7- AL-SAILAB
8- FUQR
9- LUG'AB / LUJAB
10- LIGĀM / LIJĀM
11- MA'QAM OR SUDD



1- GABW
2- MAQAM OR SUDD
3- KALB OR MASRAF
4- MARKAB
5- LIG'AB / LYJ'AB
6- SADR
7- FUQR
8- MIRWAN
9- AL- SAWM
10- AL- SHAGIB

Figure (5) Spate irrigation diversion methods used in Yemen pits surrounded by an injection recovery well field. A plan was made for the Rawadatain site (MEW 1977) to implement an artificial recharge project using the existing pits to be surrounded with five to eight wells for injecting a volume ranging from 19000 to 38000 m'/day over a four month period.

Further efforts were made in 1990 to investigate the other potential Dammam limestone formation at Sulaibiya (Pyne 1995). Two sites were tested, one at the Dammam confined aquifer, and the other at the overlying Kuwait group, containing brackish water, using three injection wells to evaluate water mixing problems.

Testing procedures included the use of sodium fiuorescein dye and tritium to assess the mixing between natural and injected water. A single injection-recovery cycle was utilized and there were plugging problems resulting from suspended solids. Test results were not conclusive (Pyne 1995) and suggested limited storage and recovery potential at the Sulaibiya site.

Qatar: Development activities in Qatar have resulted in mining of the groundwater resources. Qatar has implemented a number of measures to manage its limited water resources. One of these methods is a groundwater recharging scheme where runoff collected in depressions is diverted to a large number of recharging wells that facilitate the transfer of flood water to the underlying Rus and Umm er-Radhuma aquifers. The shallow depressions where runoff is usually collected were formed by subsurface collapse of geological structures as a result of extensive solution and removal of anhydrides and calcium carbonates. These depressions range in size from a few hundred meters up to three kilometers (Bazaraa, 1988). They are covered by colluvial soils made of calcius, sandy and sandy-clay loam.

Artificial groundwater projects using runoff collection depressions and recharge wells in Qatar were initially implemented in 1987 through the use of five recharge wells located in some of the lowland. The system was eventually expanded to include 140 wells. During the period 1977-1988, monitoring of the groundwater level indicated that recharge volume had increased by 30%. Water level fluctuations shown in Figure (7) indicate the response of the wells to rainfall-runoff events. Eight hundred new recharge wells are planned for construction beginning in 1994.

Artificial groundwater recharge schemes have been implemented to augment the natural recharge which is estimated at 42 mcm. Recharge results directly from rainfall and runoff, deep percolation of excess irrigation water and exchange with water from the deep Umm Er-Radhuma aquifers. Pilot studies of artificial recharge schemes using harvested runoff have been implemented

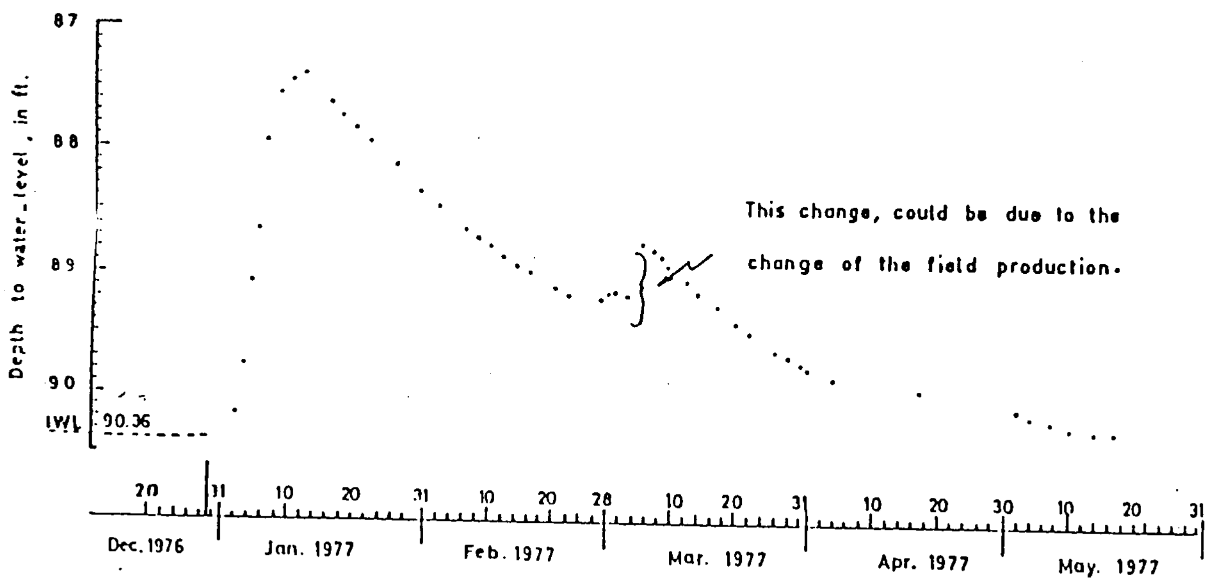


Figure (6) Change of water level in well R-39 as induced by infiltration in recharge pit of rain water, after the rain storm on 29.12.1976. (After Ministry of Electricity and Water, 1977, Kuwait) in the northern part of Qatar.

Past artificial groundwater activities in Qatar consisted of the use of a large scale flood water recharge well scheme implemented over most of the area of Qatar. More recently, a pilot recharge project has been put into effect involving large depressions where runoff usually collects and is then diverted to numerous recharging wells. The wells recharge the carbonate Rus and Umm er-Radhuma formations. Diminishing groundwater supplies have compelled authorities to evaluate the feasibility of large scale artificial recharge schemes for the building of strategic reserves. The objectives of the feasibility study is to investigate the capability of the water bearing formations to store injected water, and to determine the efficiency of removal for later use (Al Mahmood et al., 1994). The feasibility study consisted of drilling and testing of boreholes and a program of injection and water recovery test cycles at four sites. The study was implemented on the Rus and Umm er-Radhuma formations located in the northern region of the country, over a two year period from 1992-1994. The program of work consisted of drilling, pump tests, geophysical well logging, water quality monitoring, tracer analysis, many injection recovery cycles, and site modeling of both aquifers. In each site, well configuration consisted of a pumping well and three observation wells, two of which were located perpendicular to the others. In additional two wells were included, one for providing injection water and the other to dispose of water. The four selected sites represented a range of different hydrogeological regimes expected in northern Qatar. A fluorescent dye tracer was used for most of the sites to label the injected water. The results of this large scale artificial recharge study identified the layers in both aquifers as having potential for building up groundwater reserves. A number of artificial recharge scenarios were identified through detailed analysis and interpretation of data, as well as site modeling simulations (Al-Mahmood et al. 1994). The scenarios included options of recharging the aquifers from either desalinated water or imported surface water for the purposes of building strategic reserves, enhancing capacity of existing well fields, water supporting existing farms, and control of saltwater intrusion. In summary, the study identified the best areas for water injection volume and optimum methodology for water injection and recovery. The study can be used as an excellent guideline for countries of the region that are planning to undertake artificial recharge schemes.

RECHARGE SCHEME PLANNING

Planning and implementation of any type of artificial groundwater recharge scheme requires formulation of site selection criteria, field investigation,

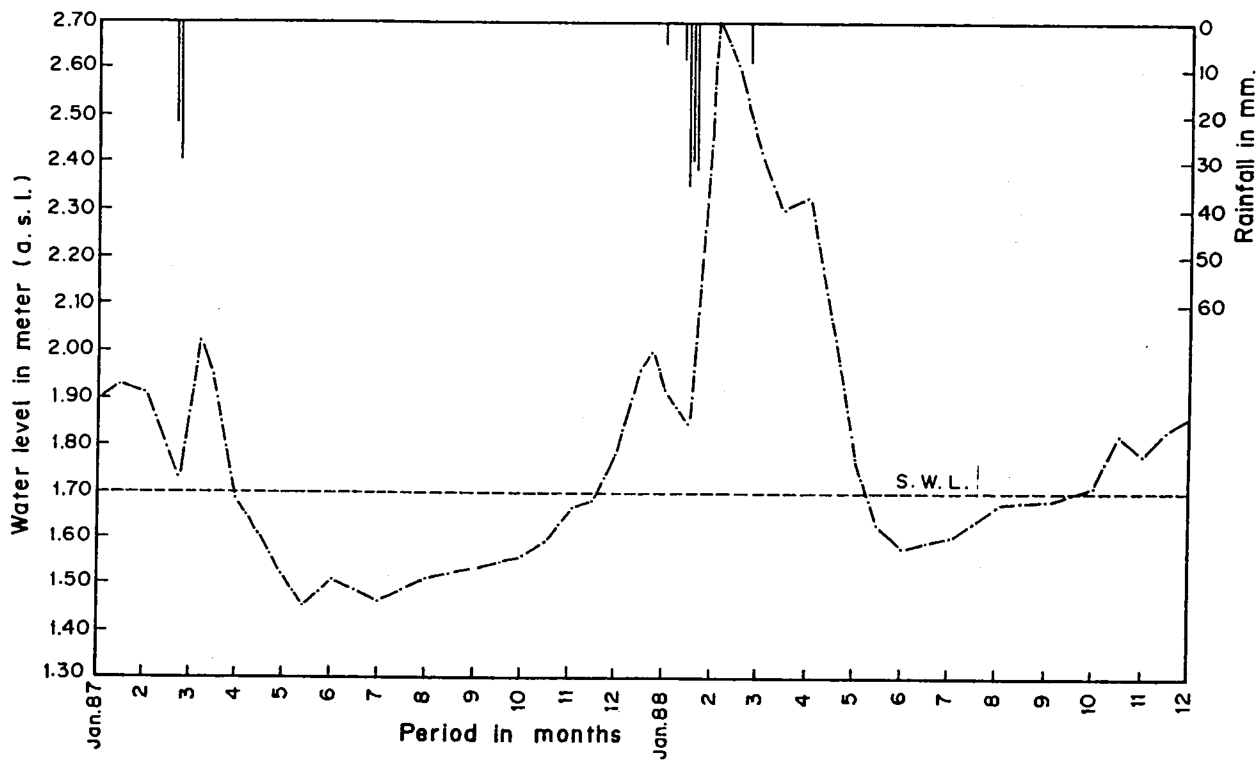


Figure (7) Well response to artificial recharge operations in Qatar facility design and implementation and operation procedures. The degree of detail required ranges from simple requirements such as spreading basins, to relatively detailed technical and advanced design criteria for dams and injection well systems. Spreading basins, some stream channel modification, pit and shaft recharging techniques may require evaluation of water supply availability and land acquisition, construction work with regard to manpower and equipment, as well as analysis of soil and bed materials and soil profile characteristics in regard to porosity and hydraulic conductivity. In addition, it is important to evaluate the groundwater aquifer characteristics with regard to availability of storage and aquifer properties representing specific yield, storage coefficient and horizontal and vertical transmissivity. However, for advanced artificial groundwater recharge techniques such as dams and injection wells, or injection and recovery systems (Aquifer Storage Recovery) further requirements in addition to the ones mentioned above are needed to design and implement such projects. Thus, emphasis will be placed on those schemes addressing their requirements, since other techniques are relatively simple and relevant information on their design and implementation is readily available in the literature. Discussion of Dams and recharge well systems will be of relevance to the needs of most countries of the Arabian Peninsula, especially those located along the Gulf.

The recommended process for undertaking artificial recharge schemes involving recharge dams, injection wells, or an injection-recovery system, consists of three phases of investigation: preliminary feasibility assessment, field investigation, and recharge facility implementation (Pyne 1995). The order of the three phases may be shifted depending on the condition of the field and the intended purpose of the project.

Feasibility Assessment: This phase involves activities addressing the recharge objectives, availability of water sources, water demand, water quality information, soil and hydrogeological characteristics, site selection, Hydrogeological analysis, conceptual design of the recharge scheme, testing program, water rights and economic considerations. It is essential to consider a range of recharge objectives and consider the most beneficial ones. The primary and secondary objectives should be identified with respect to their application to recharge dams or well systems (Pyne 1995).

The feasibility investigation should carefully assess alternative water sources for recharging the aquifer. The sources of water may be flood water, reclaimed waste water, interbasin transfers, desalination, treated drainage water or imported water. The quality and quantity of the water source should be evaluated with respect to average flow availability (volume and rate), flow variability and long term trends (drought, wet seasons, and frequency).

Water demand analysis is also required for the case where recharge water is intended for meeting water supply requirements. Analysis will help determine to a certain extent the recharge water required. Seasonal storage of water is important in this regard. The quality of water to be recharged should be carefully evaluated with regard to its compatibility to natural groundwater and plugging problems. The analysis may include seasonal quality variation and long term trends (Pyne 1995) for all sources of water in order to properly assess potentials and problems, especially for large well injection and recovery schemes. Water quality standards for different uses based on the project objectives should be evaluated in accordance with the quality of the water stored. This criteria is important particularly for water from surface sources including flood water, treated drainage and reclaimed waste water. An important quality consideration for recharge water is that injection well systems or dams produce water with high concentrations of suspended solids. Evaluation of availability of water sources and their quality will determine the potential recharge volume.

The hydrological characteristics represent one of the most important elements that influence artificial recharge. The required information include flow characteristics above and below the ground surface, as well s those in the groundwater aquifer. The flood flow characteristics influence the infiltration and percolation characteristics, especially for recharge dams. The evolution of the flood hydrograph characteristics with regard to duration, stage and volume, should be considered. The infiltration-percolation process in relationship to soil properties should be carefully evaluation. The evolution of aquifer characteristics is important with regard to recharge dams and well injection-recovery systems. The availability of aquifer storage and dispersal of water within the aquifer influence the degree of success of any artificial recharge scheme. Information is required on the aquifer's aerial extent, thickness, depth, water level, lithology, hydraulic characteristics (hydraulic gradient, velocity, transmissivity, storativity, porosity, leakage), geochemistry, number of existing wells and their production, geological structure, and the recharge and discharge boundaries. Following evaluation of this information appropriate and potential recharge methods can be identified.

Following preliminary evaluation of information, appropriate sites selection and recharge methods can be identified, such as dams or injection wells. The criteria for site selection must emphasize location near water sources, disposal of water during drilling and testing, accessibility, proximity to intended use, and land availability.

The other element of this phase of investigation deals with the design of facilities such as dams, and the type of well system. The design should include technical concepts of dam structure, layout, and material to be used. Well design includes specifications for the number of wells, drilling methods, casing, gravel pack testing and development, including cost estimation. Design features must include determination of flow rates, well spacing and arrangement, well field layout and the possibility of slacking water in multi-aquifers. Well field layout should consider land ownership, groundwater gradient, and seasonal and regional groundwater movement. The conceptual design may include model simulations of dam performance and operation, or hydraulic analysis, and well field design to be used for planning purposes. The program's baseline aquifer hydraulic testing, water quality sampling, and water level monitoring aspects must be designed in detail to be implemented in the next phase of the project. The location and frequency of data collection and sampling, as well as parameter analysis, must be identified, and the program must include monitoring activities. Groundwater simulation should include geochemical simulations and an outline testing program (Pyne 1995) which represent an important element for artificial recharge schemes. The legal aspects of ownership of the stored water should be clarified. Usually, stored water is state property, however, water rights should not be lost through underground water storage.

The preliminary feasibility phase should address environmental impacts of the proposed recharge scheme upon surface water and its quality, as well as groundwater level and quality. In case of possibly adverse effects, there is a need for mitigation plans to remedy the situation. Institutional administration of the recharge operations must be evaluated with responsibility designated to the appropriate authorities. Economic considerations should focus on the development of a preliminary estimate of the capital and operational costs involved in the recharge project.

Design features of any artificial recharge scheme must include financial implications. It is essential to analyze financial costs in relation to construction, operation and maintenance of artificial recharge scheme infrastructure, as well as assessing the expected benefits which may derive from its operation in terms of seasonal water storage, improvement in water quality, strategic reserves, and increasing supply availability. The cost analysis should include evaluation of required investment, replacement, operation and maintenance costs. Investment costs are those associated with construction of facilities including all required equipment and distribution. Replacement costs must be considered into the economic life of the project. Operational costs including administrative, energy, material, maintenance and financial requirements must be considered.

The various elements of the feasibility assessment should be compiled in a detailed report. The report should include attachments to be used for obtaining the necessary permits, institutional support and funding (Pyne 1995).

Field Investigation: The second phase of an artificial recharge scheme consists of field investigation dealing with the design and construction of testing facilities. These activities deal with injection-recovery recharge well systems. For recharge dams it represents the implementation of various construction phases of the project. Following the construction of recharge wells, site testing is implemented with emphasis on the evaluation of aquifer characteristics and behavior through pumping tests and well logging in order to determine the permeable strata. The testing program should address issues such as well plugging, geochemical effects, mixing characteristics, back flushing frequency, effective storage time and recovery efficiency. Injection tests should be performed to test the aquifer's ability to accept water. Baseline water quality characteristics must be evaluated during pumping test. A series of cycle testing consisting of water injection and recovery of water by pumping should be made for a given duration in order to estimate recovery efficiency, appraise plugging, and look for chemical reactions. Particular consideration should be given to the problem of geochemical reaction to avoid detrimental effects on the formations due to sudden changes in quality. The type of information to be collected during the testing program includes flow rate during recharge and recovery, water level or pressure in observation wells, well head injection pressure, as well as water quality parameters. The duration of the experimental testing of recharge schemes should be decided according to field conditions. Data collection and analyses should be documented in technical reports.

Implementation: The final phase represents the design and implementation of the recharge scheme including support facilities. Implementation consists of the construction of the groundwater recharge scheme and its operation. The recharge scheme should also address operation and maintenance requirements. The operation and maintenance program should consider to periodic changes in operation mode (recharge or recovery), backflushing to remove sediments from the well, short time pumping, and well development. It is advisable to provide a disinfectant residue consisting of chlorine or chloramine within the casing, screen and gravel pack to control bacterial activities. The implementation phase should also involve a monitoring program.

SUMMARY AND CONCLUSIONS

Countries of the Arabian Peninsula have concentrated their water management efforts on the development of water resources and the construction of support infrastructure. During the past twenty years significant achievements have been made towards the provision of safe and adequate drinking water supplies, especially within the GCC countries. Irrigation in the agricultural sector has also been encouraged to promote self-sufficiency in farm products. Activities in all sectors have contributed to increased water consumption and depletion of water resources. Little effort has been made to manage water resources, or to set up short and long term strategies or policies in order to avert future water deficits. In addition, emphasis has not be placed on the importance of supply and demand management issues, by either the public or decisions makers, as essential tools to reduce water deficit and preserve water for future generations. Some important demand management techniques such as public education, water survey technology, efficient plumbing codes and regulations, and water pricing, have only been implemented in a fragmented fashion, and not on a comprehensive and integrated basis. The same is true of water supply management using a number of methods including supply augmentation through artificial recharge schemes, weather modification, system rehabilitation, reuse of waste water, and protection. These resource enhancement techniques have only been implemented on an infrequent basis in some of the countries of the region. Fragmented implementation has not brought about optimal development and utilization of water resources, including desalination and treated waste water.

The countries of the Arabian Peninsula, because of their limited water supplies, should focus their priorities on the integrated water resource management approach, including a shift in sectoral water allocations. There is a need to vigorously pursue any and all means by which water demand could potentially be reduced, as well as methods for augmenting supplies. The various artificial groundwater management techniques presented can be successfully applied in most parts of the region, provided that they are integrated into the national water management system. Groundwater management schemes also require efficient operation, continuous performance evaluation, and implementation of remedial solutions for continued improvement; issues which have not received adequate attention in most of the ESCWA countries where recharge facilities exist.

The potential benefits of artificial recharge are numerous, however, selection of techniques must address short and long term objectives of the national water policy. The artificial recharge techniques most suitable to the countries of the Arabian Peninsula are recharge dams, spreading basins and injection-recovery well systems. Whenever appropriate, such techniques must be utilized on a continuous basis in order to prolong and preserve natural water sources. The benefits of these techniques have been demonstrated through their ability to achieve overall improvement in storing some of the available water from natural sources. However, given the magnitude of the available water resources, including runoff and reclaimed waste water, the countries of the region are still far from achieving optimal water storage, utilization and management of resources. Further action is needed to accelerate the implementation of suitable artificial recharge methods. In addition, consideration must be given to the financial implications with regard to the cost of recharging water using different methods, as well as the cost of recovering the recharged water.

We should not focus entirely on the option of artificial recharge techniques to augment supplies, but should direct our attention to the true causes of water deficit. In this regard, instead of using artificial recharge to build groundwater reserves, we could manage the aquifer through control of pumping, or designating an aquifer as a strategic reserve to be used during times of urgent need. Another option includes the reappraisal of current agricultural policy, particularly in areas where irrigation accounts for the majority of water consumption. In this case, a shift in priority to other sectors which use less water could be appropriate. Other possibilities include the application of a water surcharge to reduce consumption in all sectors, or the use of reclaimed waste water for irrigation and industrial purposes while preserving potable groundwater for domestic use. Careful assessment of all feasible options, including artificial recharge, must be carried out within the context of the national water policy, and the development of integrated water management plans addressing short and long term goals must be adopted in the immediate future in order to preserve and prolong the regions limited water resources.

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Streamflow Records for the Wadis of Oman

Aysha Al Khatry and William O'Brien

STREAMFLOW RECORDS FOR THE WADIS OF OMAN

Aysha Al Khatry and William O'Brien
Data Processing Section, Surface Water Department
Ministry of Water Resources, Sultanate of Oman

ABSTRACT

The wadi valleys of the arid country of Oman are usually dry, but when the rains fall the resulting flash floods can be devastating. It is the task of the Ministry of Water Resources (MWR) to measure these flows. A network of wadi gaugès was initiated in 1974 to record depths of flood water, which are used to calculate volumes and peak rates of flow. Oman's rugged conditions make this a challenge for the flow measuring equipment and the hydrologist alike. Flow rating curves, that compare depth of water to flow rate, have been developed for each gauge, mainly by indirect estimates of the larger flows and direct measurements of the smaller flows. Conscientious field work is required for the indirect estimates of flow, especially the surveying of high-water debris marks required for the slope-area method, and to make the direct measurements, such as by current meters. The routine field inspections are particularly important to ensure that the gauges are calibrated and recording properly, ready for the next flood.

MWR has developed an automated, interactive process for computing the wadi flow records. The process of computing wadi flow has to accommodate effects of shifting and scouring channels, sedimentation, powerful hydro-dynamic forces that can bend or destroy the gauges, 50^{0}C summer temperatures, and long dry periods with sudden wetting cycles. By 1996, the Surface Water Department network had 143 gauges. Most of the gauges have dataloggers for continuously recording water depth, and the readings can be easily downloaded to computers. Quality control checks along the process attempt to make the best use of the field data, and develop the best estimate of flow possible. There are places to make improvements, but Oman has achieved a great deal on the road to quantifying her wadi flow resources.

Keywords: streamflow records, stream gauging, flash floods, wadi, hydrologic data processing, arid hydrology, Oman

INTRODUCTION

Oman occupies the southeast corner of the Arabian Peninsula. The climate is considered hyperarid, with highly variable rainfall that averages about 100 mm/year, while potential evaporation is almost 3000 mm/year. Groundwater is the main water source, harvested by wells or by falaj (*ganat*) collector tunnels. The irregular rainfall makes groundwater storage all the more valuable, providing a buffer for low rainfall periods. Recharge of the groundwater mainly occurs along the active wadi channels and by direct recharge in actively irrigated areas. There is evidence of some direct recharge in karst limestone areas.

When rainfall occurs, the normally dry wadi beds fill quickly and a wave of sediment rich water advances downstream. Hydrographs are usually characterized by sharp peaks and duration less than 1 day. The sharp peaks are due to Oman's unique topography and rainfall pattern. The watersheds are fairly steep, there is little vegetative cover, and the orographic effects of the Oman mountains cause moist air from tropical depressions to produce high rainfall intensities. Water levels in some narrow wadis has been known to rise quickly, capturing vehicles, livestock, household furnishings, and even people, carrying them downstream. Recently a number of tourists were tragically caught by a such a flood and drowned.

Most of the wadi gauges are located where the mountain jabals approach the alluvial fan. At the gauges, the bed slopes are usually mild, flow is sub-critical and the peak flow velocities are on the order of 1-2 m/s. Further up in the wadis where the slopes are greater, flow can be supercritical with higher velocities. Wadi floods dissipate as they flow from the jabals onto alluvial fans where the flow infiltrates and spreads to the multiple and braided channels. Many of the alluvial fans are considered active, being reworked by the larger floods, with flow following one set of channels one time, and alternative channels another.

Since 1974 the Government of Oman has installed wadi gauges to provide flow and flood data upstream of developing areas and structures, such as dams or major highways. Some gauges were sited to fill gaps in the national coverage of catchments for assessment of surface water resources. By 1996, there were 143 active wadi gauges in the Surface Water Department network. There are an additional 29 wadi gauges for inflow measurement at the existing dams that are managed as a separate network. The Government has maintained its commitment to wadi gauges for over 20 years and is now just beginning to reap the rewards of using the data collected. The locations of the current national wadi gauge network in Northern Oman is shown in **Figure 1.**

The degree of confidence that can be placed on the data is directly proportional to the quality of the data. Quality control steps are built into the data processing. Two main levels of checks are institutional, the field work is checked by one set of staff at MWR headquarters, and the processing of the data are done by another staff group. This allows questions to be asked and results reviewed before the data is released to other MWR departments, consultants, and other governmental or private agencies. In Oman's conditions quality control steps will always be necessary.

This paper summarizes the wadi flow computation process and emphasizes the quality control steps currently being undertaken for the Surface Water Department network. Wadi flow records require a team effort, from the regional field staff who inspect and maintain the gauges, to the staff who check the field work, to those who do the processing and reporting. There is room for improvement and recommendations are made. Lessons from Oman's experience may be useful to hydrologists and hydrographers in other arid regions.

Purpose of Wadi Flow Data

The wadi data are necessary to predict frequencies and magnitudes of flood peaks and volumes, that provide the basis for engineering designs or operation studies for road crossings, culverts, bridges, dams, and flood protection schemes. Good flow data are needed so that structures are not underdesigned, which would result in suffering and damages that can be in millions of Riyals. Conversely, good flow data are needed so that structures are not overdesigned, which can result in excessive construction costs.

Flood volumes are needed to quantify water lost to the sea or desert, and to estimate groundwater recharge and surface water components of water balances. They can be used to check the changes in falaj flows or groundwater levels. They can also be used to apportion water rights or provide limits for diversion projects. Flood plan management depends on wadi flow data to plan what land can be developed and assign insurance risks. This is especially critical in heavily developed commercial areas.

As the length of flow records increase, planners and engineers can make more accurate estimates and plan economics of projects more confidently. Length of wadi flow records for over 90% of the wadi gauges in Oman is less than 15 years, and they are just beginning to show trends and provide initial estimates of frequencies.

WADI GAUGING NETWORK

The wadi gauging network was initiated in February 1974 by one of MWR's predecessor organizations. Sixteen wadi gauges were installed that year. Many estimates of peak discharge at scattered locations were made by making use of high-water trash marks for "indirect" flow estimates. Dates for the flows that created the high-water marks were collected from rainfall records and interviews with local citizens.

Estimates of peaks and flow volume were also made using a channel geometry technique that had been developed in the western United States (Johnson, 1977). A definite relationship was found between the channel geometry and flood frequencies in the mountain areas above the coastal plain. This was recognized as a "stop gap" measure until more slope-area points could be collected to develop rating curves and more recording gauges installed.

The severe floods of 1976-77 knocked over and destroyed some of the early wadi gauges, but the determined hydrologists and technicians learned from this and installed more robust gauges to replace them. It quickly became apparent that Oman's floods were near the world maximums for a given catchment area (PAWR, 1983), and careful selection of sites and use of rugged enough equipment would be necessary.

The gauge sites were selected to measure depths of flow upstream of developed areas or places where assessment of surface flows was planned. Sites needed to have good access, even in wet periods, and have a fairly straight reach adjoining where slope-area or other indirect methods could be used to estimate flows. The slope-area method assumes uniform flow, so the reach should not have dramatic contractions or expansions, and the slope should be fairly constant.

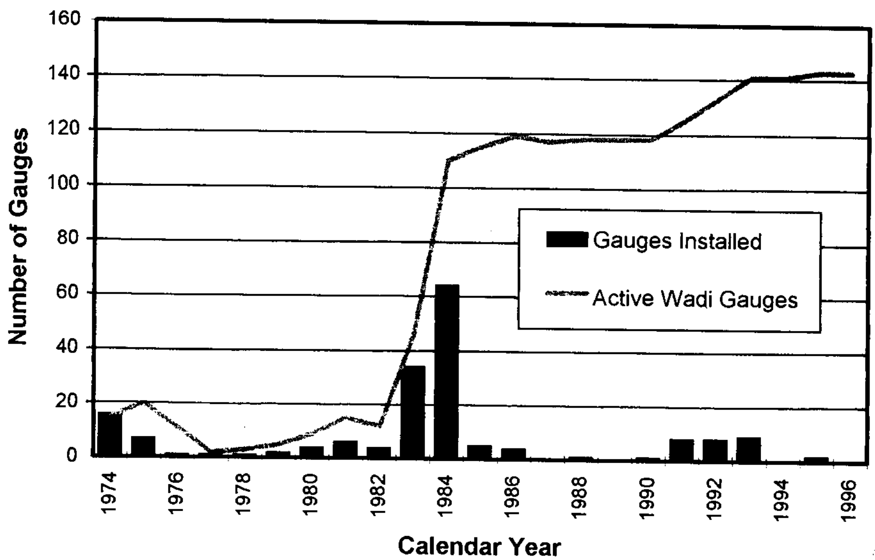
The first wadi gauges were all float gauges, with tall standpipes and strip charts. A few bubble-gauges were added that did not need the expensive standpipes, but they also had strip charts. Dataloggers, also called by their trade name "Datapods", were first added to the network in 1980, and had the advantage of quick computer downloading of flow depths. Maintenance for all the gauge types is a major concern.

With time, many of the older float and bubble gauges have been relegated to back-up gauges for the datapods. The datapods require a fair amount of maintenance and have some difficulties of their own. The datapod transducer measures the depth of water above it by recording pressure. Sometimes silt builds up around the transducer casing and gives false readings and negative overshoots on the downside of the hydrograph. Other times there are cycling and drifting of the record when there is no flow. This may be caused by temperature and humidity and indicates better maintenance is needed. Dataloggers have become the preferred instrumentation for Oman's conditions.

Crest stage gauges, that only record the height of the peak flow, were installed to check the continuous recording stations and at wadis where a full station was not justified at the time. The crest gauge station collects peak data that can be used for frequency analysis or to develop a rating curve if a recording station is later installed.

The network has expanded to 143 wadi gauges by 1996. There are 103 datapods, 17 float gauges, 5 bubble gauges, and 18 crest-gauge stations. The numbers of wadi gauges grew gradually in the first years, then a major investment was made in 1983-84 to expand the network. **Figure 2** shows the historic development of this network and the total number of active wadi gauges. Plans are being made to expand the network by 60 more wadi gauges over the next 5-year plan.

Figure 2: INSTALLATION OF WADI GAUGES
(Surface Water Department Network)

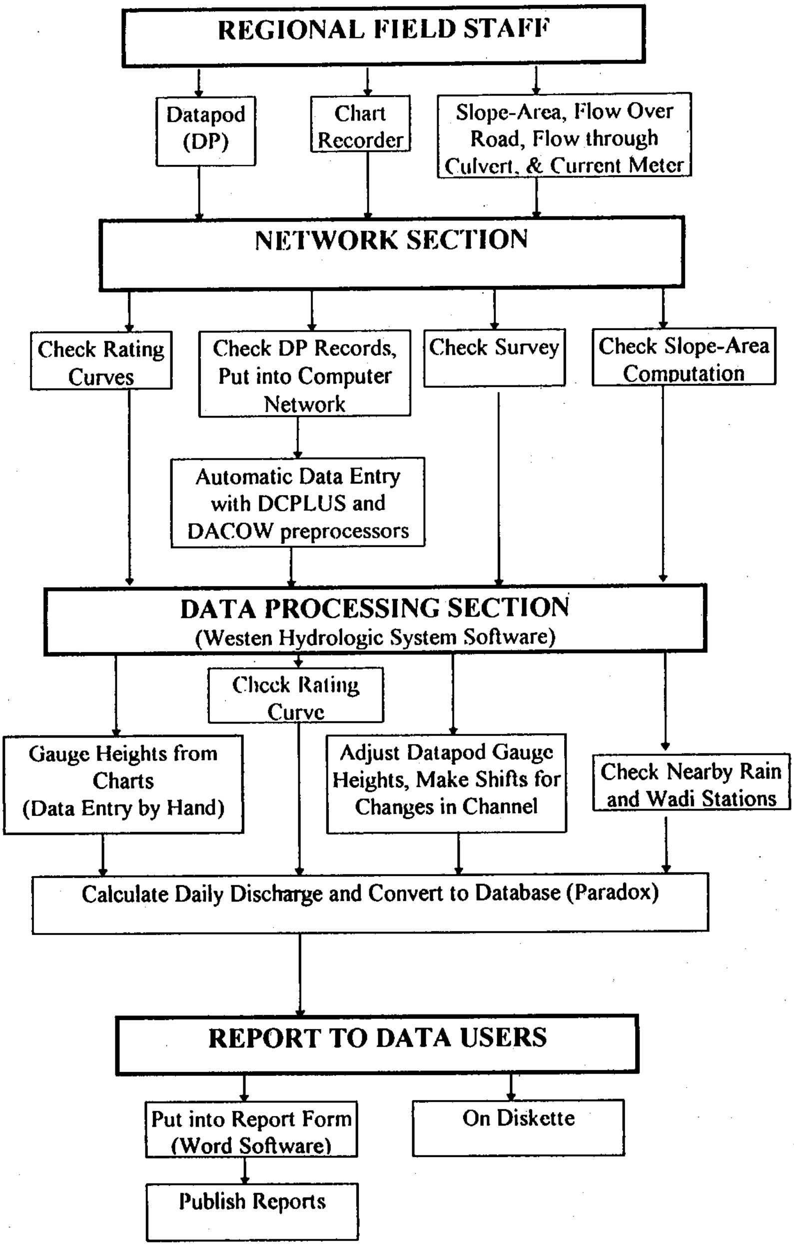


DATA PROCESSING

Wadi data take a many-stepped path after they are collected from the field. **Figure 3** shows the process from field to user reports, and the three main staff groups involved. Oman's conditions require a number of checks and adjustments to the field data. In many temperate countries with regular river flow, a routine

FIGURE 3:

PATH OF WADI DATA



and automatic record can be established. In Oman, the story is more complex and challenging.

Institutional checks were established by having three staff groups work on the data. Further checking and quality control is done within each group. The first group, regional field staff, collect the data and make surveys and observations of the gauge that help in estimating flow. The next group to see the data are called the "Hydrometric Network Section" at MWR headquarters. They check the field data and get it into the filing and computer systems. A third group, the "Data Processing Section" check the data, update the rating curves, calculate flows, enter the results on a database, and finally publish the data.

Field Data Collection

Field staff for wadi gauges are located at 7 of the MWR regional offices scattered throughout the country. At each office, there is one Regional Hydrologist with supporting technicians who inspects the wadi gauges monthly and after major flood events, collects the chart record or datalogger chip, arranges for maintenance, makes indirect or direct flow estimates, and sends results to MWR Headquarters. These staff know the wadis and gauges very well and can be called upon to explain why the gauge record behaves in a certain manner. They can explain such problems as flow below the level of the orifice, flow bypassing the gauge, bent crest gauges, damaged gauge housing, sediment covering the transducer, backwater effects of culverts or bridges downstream, irrigation return flows, etc. Good field work means less estimation when computing the records.

The main field technique used in Oman for indirectly estimating flow is the slope-area method. This method is based on the Manning's equation and the principle of conveyance. It is an appropriate indirect method for Oman because it only requires surveying of a few cross sections and making an estimate of roughness. Sometimes more than 3 cross sections are required if the hydraulic profile has irregularities. The accuracy of the estimate depends on the ability of the hydrologist to select high-water marks and to draw representative water surface profiles (Dalyrmple, 1967). Estimates of roughness, Manning's "n", are made in the field, which are usually in the 0.035 to 0.040 range. A few gauges have had more thorough surveys and step-backwater analysis was done using HEC-2 software. Use of these techniques require well trained field staff.

Other indirect methods of flow estimating are employed if possible, such as using a weir estimate for flow over a roadway crossing, or hydraulic equations for flow through culverts. Appropriate application of these methods and quality of the calculations is an area that MWR is trying to improve upon.

The quality control of the field work was most successful when there were staff from MWR headquarters who made site visits with the regional staff, evaluated their performance, and upgraded their training.

Initial Checking of Field Data

The field data and inspection forms are checked by MWR headquarters staff of the Network Section and filed by each gauge name. The datalogger records are transferred to the computer network by pre-processor software written by MWR. Quality control measures are taken, such as recalculating the slope-area survey or current meter measurements. Comparison between water elevations from the datapod, crest-gauge, and high-water marks are made. Survey notes are checked for reference points and elevations. Field staff may be called to answer questions.

Computation of Discharge

The "Data Processing Section" are the staff who pull the field data together and calculate flow. The process is automated using the Western Hydrologic System (WHS, 1991) software. All normal gauge heights from charts and dataloggers can be entered into the program. Stage versus flow rating curves, stage shifts and datum corrections can be entered and incorporated into the calculations. When the chart or datalogger is not working, estimated flow is based on nearby gauges and rainfall stations. Of the daily flow volumes calculated, about 20% have been estimated.

Early on it was recognized that checking and rechecking the discharge computations was necessary because of the potential for misinterpreting the field data and the desire for confidence in the results. For most gauges, there are a number of assumptions that go into the computations that need to be made. It increased the confidence in the data if those assumptions were checked. Each staff is accountable for his judgments by signing his initials on each step of the analysis. A reviewer also signs his initials as he checks each step of the analysis, and then he enters the data into the database. A third reviewer checks the database entries and prepares the report summary. Finally, a fourth reviewer checks the reports prior to publication.

The number of reviewers requires a staff team and means that results take time to reach the publication stage. For urgent requests, data are computed by one staff and the results stamped preliminary.

Results of the discharge calculations are transferred to a PARADOX database for storage and retrieval. This database is starting to outgrow the capacities of PARADOX. A new database is being designed that will be ORACLE based.

Users often request data on diskette. MWR provides this from the database, usually in ASCII or DIF formats.

The reports have been developed with the user in mind. Data are provided as daily, monthly, and yearly discharge. Gauge description, history and lists of peaks above a certain base are also provided in the published reports. A station analysis report is written for each gauge file to explain deviations from the standard analysis process and to document assumptions or unusual situations.

ACCURACY OF WADI DATA

The accuracy of the calculated flows depends on the quality of field measurements and how well the hydrologist understands and applies the shifts and corrections to the record. Field inspection notes and communication between the field and the data processors is critical. There are periods where the stage recorders are not working properly. These periods can be kept to a minimum by alert field staff, but whatever records are lost have to be estimated.

The field measurements are each given a rating for dependability. If field marks are clear and consistent, the measurement can be rated "good". Most field measurements are rated good or the next level "fair". Where there is no data record the estimates generated are usually rated "poor". For indirect measurements, such as the slope-area method, MWR (June 1996) estimates that good measurements are probably within 10% of the true discharge, fair are within 20% and poor are greater than 20%. A good current meter measurement is probably within 5% of the true discharge, while the fair are within 8%, and the poor greater than 8%. There are probably some compensating errors over the course of years and the long term rating curve should be quite reliable. Gauges with shifting wadi beds present less reliable data, as well as the gauges with wide cross sections where flow changes greatly with small changes in depth, and side channels may miss the gauge. In published data reports, every gauge is assigned an overall rating, of good, fair , or poor to give the data user a feel for reliability.

Most of the flow gauge records are less than 15 years long, and only one gauge has a record greater than 20 years. This is an extremely short database period for predicting flood frequencies. Generally, one can not extrapolate return periods for more than twice the record length, which for Oman means that predicting the 50-year event is all that can be predicted with much confidence.

CONCLUSIONS AND RECOMMENDATIONS

MWR has developed a significant national wadi gauge network that has begun to characterize and quantify Oman's flood resources. The early flow estimates by channel geometry have been replaced by real flow data and many wadi records are now more than a decade long. A long term commitment to surface flow gauging will be needed to provide the kind of data required for reliable engineering and planning studies.

The importance of the field work and the rugged conditions are persistent reminders to seek better methods and procedures. Reducing the amount of estimated discharges below the current 20% is a challenge for equipment and field staff.

Field work efforts could be enhanced by use of electronic surveying equipment. This is expected to upgrade the quality and speed of surveying required for the indirect flow estimates, and allow for more cross sections to be made. Further visits to field staff by headquarters staff, and further training of the field staff in the slope-area and step-backwater methods are recommended. The slope-area techniques can be refined, especially if more cross sections can be routinely surveyed. Step-backwater analysis (routing) using HEC-2 or HECRAS software can be carried out to check rating curves.

Some research at "test reaches" and "representative basins" would be helpful. Manning's "n" changes with flow and so does the shape of the channel cross section. Research directed at quantifying these effects might result in adjusting rating curves. Intensively gauged "representative basins" would shed light on rainfall/runoff relationships that might help in estimating flows during periods when a gauge is not operating, or in un-gauged wadis.

Quality of the data would be improved if more hydrologic comparisons were made with nearby rainfall and wadi flow gauges. This is being done to some degree, but it is hoped that as regional assessment studies, flood frequency and other analyses are carried out, anomalies in the data will be discovered and set aright.

The proposed upgrade of the database to ORACLE is strongly supported. This should accommodate the growing size of the data base, benefit data processing, and preparation of reports. As the data processing system evolves, further training of technicians and updating of the Hydrologists manual (MWR, 1996) will be necessary.

ACKNOWLEDGMENTS

The authors wish to thank staff and colleagues at the Ministry of Water Resources for their assistance and comments on this paper. Particular recognition and thanks goes to the dedicated and often unsung field teams who have installed, inspected and maintained the wadi gauge network over the last 20 years.

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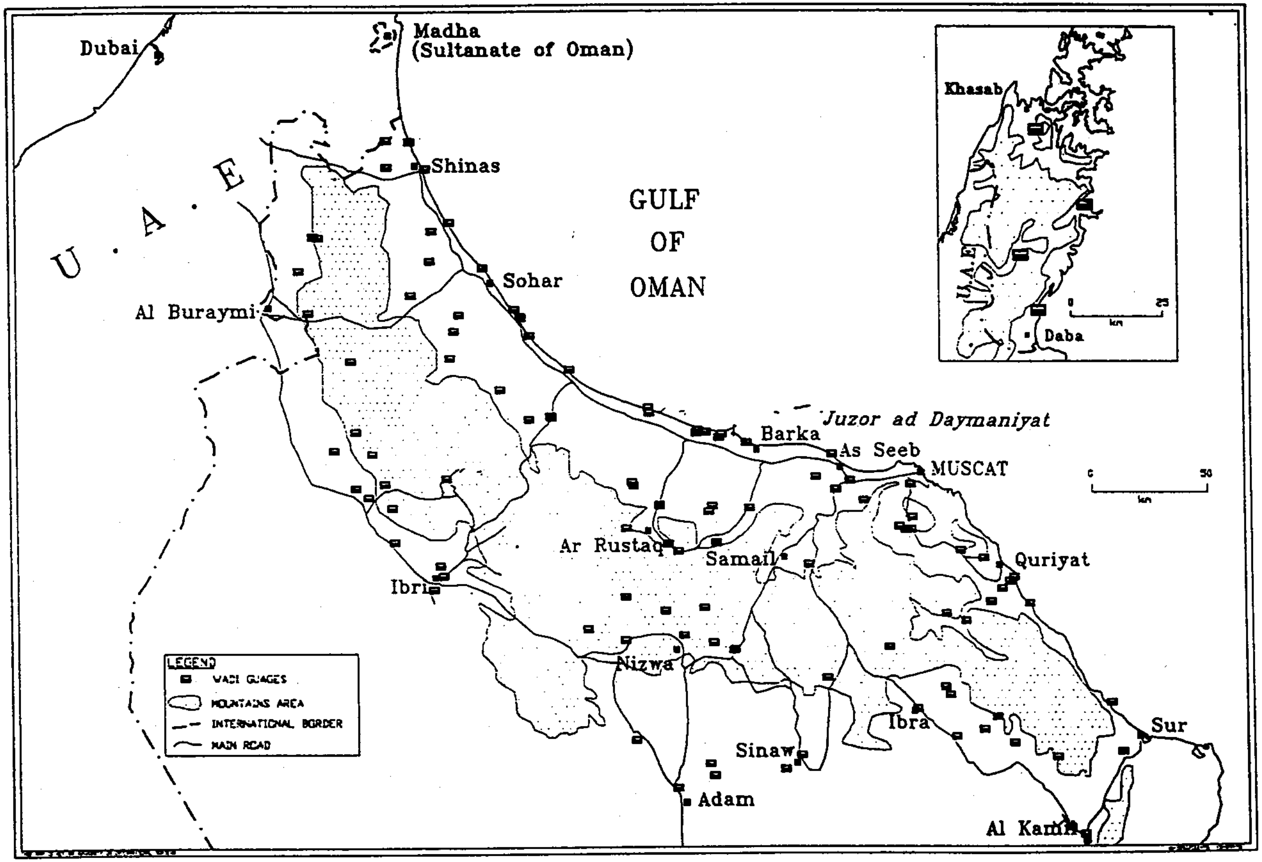

FIGURE 1. LOCATION OF WADI GUAGES IN NORTHERN OMAN

GROUNDWATER RECHARGE DAM AND HYDROGEOLOGY OF WADI AL-FULAYJ, WILAYAT SUR, SULTANATE OF OMAN

Majid Bilarab Al-Battashi and Syed Rashid Ali
Dams Department
Ministry of Water Resources, Sultanate of Oman

ABSTRACT

Groundwater, the main source of supplies to the irrigated agriculture in the Sultanate, is limited and affected by uncertain drought cycle and the increasing rate of exploitation due to fast growing needs. To overcome the resulting problems, like deficit of resource, deterioration of groundwater quality, encroachment of sea water, decline in pumping level etc., a number of groundwater artificial recharge schemes, in different parts of the Sultanate, have been executed through systematic studies covered under National Development Plan. The technique involved temporary detention and slow release of the flood water at a suitable location of catchment, of a wadi to allow more replenishment of groundwater in the exploited areas. The studies on the groundwater recharge scheme at Wadi Al-Fulayj were undertaken through the services of Consulting Engineers Weidleplan. The feasibility and design studies were completed by August 1990 and identified dam location about 10 km upstream from the coast on the main Wadi Al-Fulayj and on long term, envisaged an additional recharge of over 2 million cubic meter (MCM) per year to the aquifer. The construction of a recharge dam of 430 m in length, 3.5 m high and a designed storage capacity of 0.78 MCM was completed in December 1991. The dam became operational in February 1992, since then many floods of different sizes have occurred and monitored at the dam. The established observation network under regular monitoring by the Dams Department, Ministry of Water Resources in the Sultanate of Oman, includes a flow gauge at the dam site, 21 drilled and 6 dug wells in the downstream recharge area. Presented in this paper is an account of hydrogeology of the recharge area. A synthesis of the available monitoring data is made in conjunction with the hydrogeology. A sustained recovery of water levels and improvement in water quality has been monitored in the target (irrigated) areas of the recharge dam.

INTRODUCTION

Wadi Al Fulayj is within the Sharqiah Region of Northern Oman draining a catchment of 750 km^2 in the Gulf of Oman (Figure-1). The area is defined by the Jabal Khadar on the North-West, the Jabal Tawa on the West and Jabal Khamis on the Eastern boundaries of its catchment. Sur at the coast is the developing town, as the headquater of Sharqiyah Region. The irrigated agriculture in the coastal area of Wilayat Sur, being dependent upon water supplies from shallow and limited thick alluvial aquifers of Wadi Al-Fulayj; suffered periodic constraints resulting from high variability of catchment rainfall. Years with below average precipitation or dry spells experienced deficit of resource as well as notable change in the quality of ground water due to upconing of underlying saline water and inland intrusion of sea water in the irrigated areas. In as much as any individual torrent event in a year could be little effective towards replenishment of ground water, with more runoff to the sea. The conditions could only be improved in a year having successive flood events.

These factors in the absence of any management of the resource effected the crop yield, reduction in the cropped area, and at places temporary abandoning of farms. The cultivated area in Bilad As Sur spread over in 546 farms as (old 504 and new 42) covered 655 hectares of land. Out of old 43 farms covering 51 hectares were reported abandoned on account of deteriorating conditions (Agriculture Department, 1989). Between the observed period (1975-1982) Hydroconsult in their study indicated an increase of electrical conductivity of ground water in the old garden area due to the combined effects of over pumping from wells and sea tides that encroched up to 1.5 km inland from the coast. Ground water from over 70% of wells had electrical conductivity values more than 3000 μmhos/cm. Given due priority the Ministry of Agriculture & Fisheries included the area under the programme of studies of recharge schemes to identify the feasibility of a detention dam on wadi (catchment 677 km^2) that could eventually be a measure to combat the water salinity and water deficit problems over the irrigated lands.

Based on a preliminary studies (1982) conducted by Hydroconsult the Ministry of Agriculture & Fisheries carried out feasibility and other detailed studies in 1989 for the recharge scheme through the joint services of Weidleplan & Hydroplan (WHJV) as Consulting Engineers. The scheme proved to be technically feasible economically viable at a location 10 km upstream from the coast on the main wadi. Under the supervision of Weidleplan & Hydroplan the construction of the recharge dam started in 1991 and completed by December 1992 through the contractor Wimpey Alawi LLC. Wadi Al-Fulayj dam having a height of 3.5 m, length of 430 m and a design storage capacity of retaining 0.78 MCM flood volume, became operational in February 1992.

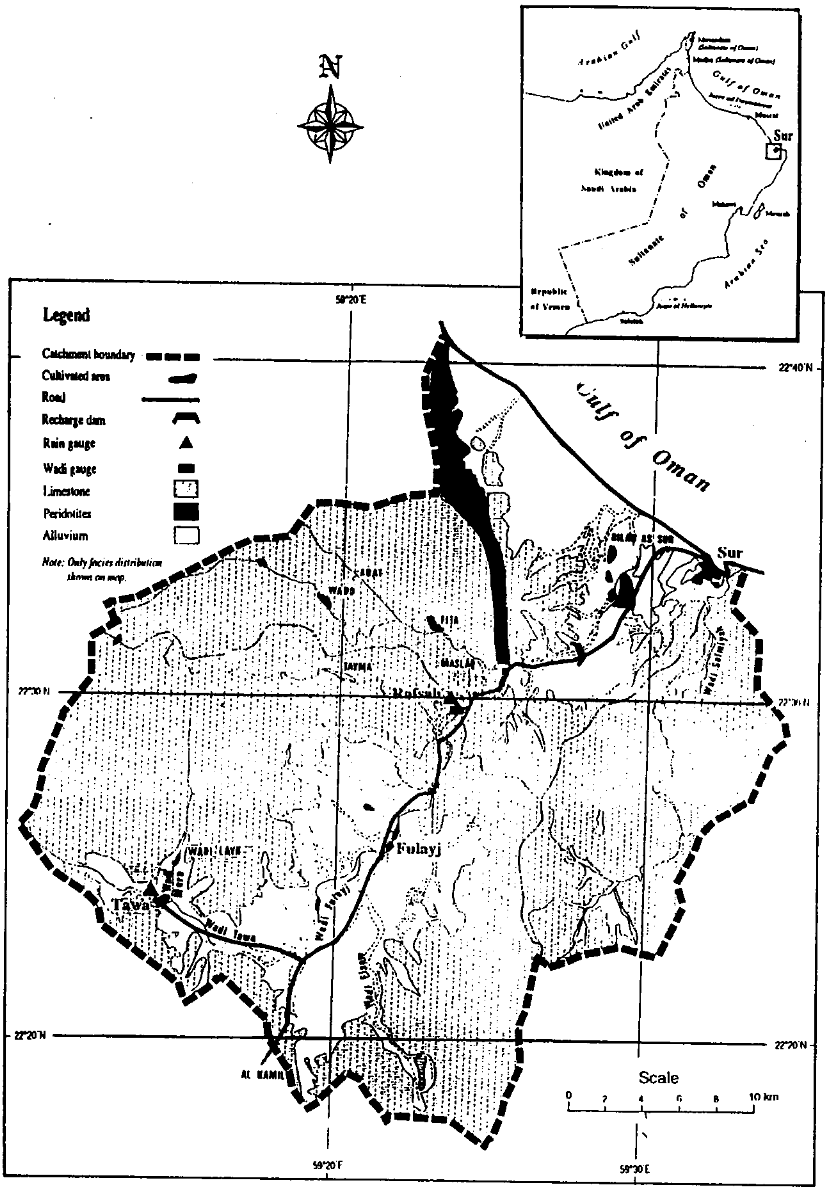

Fig. 1. Map showing Wadi Al-Fulayj (Sur) Cathcmen area

THE RECHARGE DAM

Wadi Al-Fulayj Dam is located in Wilayat Sur about 10 km upstream from the sea coast and 3 km upstream from the Bilad As Sur gardens in the main wadi. The structure comprises an earth fill dam with a concrete spillway built, across the valley and a down stream stilling basin made of rock fill gabions. The dam has a storage capacity of 0.78 MCM. The spillway, with provision of two controlled outlets (dia 0.8 meter) is 430 meter long and designed to discharge a maximum flood of 6600 m^3/s.

Objectives & Approach

Since the commissioning of the dam in February 1992, the rainfall over the catchment resulted in several floods in the dam during hydrologic years. Since then floods reaching the dams have been monitored in addition to the routine monitoring of water levels, water quality from an observation network in the down stream areas of recharge dam. The study, in this paper focuses to present the following:

- Dam performance and catchment hydrologic response in the initial years of operation.
- Preliminary evaluation of the impact of dam as increase in potential and improvement in groundwater quality.
- An overview of the hydrogeology of the area, and changes in groundwater regime after the inception of dam.

The present work is based on the syntheses of monitoring data, an interpretation of hydrogeological, hydrological conditions and review of the various reports listed under reference. Hydrogeological interpretation has been carried out with the help of updated investigational data and historical records on water levels, and water quality from observed wells. The analysis of the stage hydrographs from reservoir recorder provides an estimation of amount and duration of flood for each event reaching the dam and its release in the wadi as infiltration to the aquifer in the recharge area. The study of well hydrographs, on water levels, water quality for the recorded period, with the present knowledge on aquifer potential, and present water exploitation leads to estimate the artificial recharge from the dam.

Previous Works and Data

Investigation studies involving geophysical surveys and water sampling were conducted in the area in 1975 by Consulting Engineers Renardet Sauti as a part of overall Water Resources Survey in North-East Oman (Interim Report, 1975).

Based on well covered electrical resistivity surveys but with no drilled bore control at that time, the nature and probable depth of the alluvial cover has been defined. Hydroconsult the Consulting Engineers in 1985 carried out further preliminary studies on water resources in the area. This included detailed water quality sampling from wells in addition to topographical surveys and testing of dug wells. The studies provided basis for terms of reference for the Feasibility Studies of Recharge Scheme that were initiated in 1989 and completed in 1990 through the services of Weidleplan & Hydroplan as consulting engineers. Various kinds of surveys and exploratory drilling in the recharge area included as a part of the studies. The consultant in the target area installed eight wells (STW 1-1 to STW 5-2) and ten observation wells (SOW 1-1 to SOW5-2) for aquifer testing. All these hole finished within a depth of 45 meter. These are now put to use as monitoring wells with an addition of 6 more wells drilled by the Dam Department in 1993, 1995 as network upgradation. The Ministry of Electricity and Water (MEW) developed well field (SE-1 to SE-6), expanded by five more wells in 1995 all located downstream to dam. These wells supplement water supplies of Sur town in addition to from the desalination plant.

ENVIRONMENTAL SETTING

Physiography and Geology

Wadi Al-Fulayj with a total drainage area of over 750 km^2 constitute a hydrologic basin of the coastal drainage system of Sharqiyah region of Oman (Figure 1). The larger part of catchment is covered by rocks as cliffs or low hills near the coast to the high peaks rising to elevation of 2327 meters above sea level in west and southwest. Elevations are lower along the south and eastern boundaries where the maximum elevation in the southeastern corner of the catchment is 1076 meters above sea level. In general the catchment area consists of steep to moderate mountainous terrain in the head of catchment and gentle slopping alluvial plain near the coast. A distinct feature is the change in shape of the valley in response to the change in geological formation and structure. Few kilometers upstream of dam the valley becomes narrow in the relatively resistive rock outcrop separating the upstream valley flat from the coastal flat. For the purpose of this report the alluvial area of coastal flat downstream to recharge dam, being under the impact has been considered in the report.

Sheet No. NF-40-08 (Scale 1:25,000) published in 1992 by the Ministry of Petroleum and Minerals, Sultanate of Oman provides an overview of the geology and structure of the area. The rocks expose in the basin are of sedimentary origin belonging to Tertiary Age. Geological formations exposed over the large part of the catchment includes Usawa and Abat formation (Early-Middle Eocene) represented by bioclastic marl, marly limestone, calcarenitic beds, with subordinate sandstone, silt stone and yellow glauconitic marl. Bedrock hills of Abat Formation separate the upper and lower catchment. Elsewhere the rocks of Tahawa Seeb formations include polymict breccia olstoliths marl, bioclastic limestone and conglomerate. Commonly the rocks dip at gentle angle and vertical faults develop in southwestern part of the catchment.

Because of the types of rocks with less common structural features like joints and faults, the points of natural ground water discharge like springs or falaj are not common. Also that the sedimentary rocks is likely to yield water in a drilled well is not known through any investigation. The unconsolidated deposits (recent to sub-recent) of alluvial material, of thickness ranging within a maximum of 80 meters are found along the wadi. Downstream to the dam, the alluvial fill widens towards the coast following the valley, flanked by marly outcrops. The wadi exit near the coast develops a lagoon shape where flood water accumulate. This is partly also the effect of a dam constructed in 1975 for protection against sea tidal action that encroached up to 1.5 kilometers inland. The unconsolidated deposits constitute the principal aquifer and reservoir to ground water in the area.

Hydrology

Catchment Rainfall

Due to arid climatic conditions the rainfall over the catchment is low and erratic and varies both seasonally and as total annual. The catchment could be divided into two principal areas; an upper regime (above 600 mASL) and a lower regime (below 600 mASL). Rainfall tends to be higher in the upper regime and runoff is greater due to the low permeability rock, steep slopes and almost no vegetation. In the lower regime there is less rainfall and runoff is lower because slopes are gentle (less then 1 %) and the soils are permeable. Rainfall data for the three stations in catchment located at Tawah, Fulayj and Sur is available since 1974 for the later two stations with missing gap, and since 1981 for the station at Tawah. These data are not sufficient in time span and its quality to derive the hydrologic parameter of the basin.

With such limitations, the statistical approach to identify the probable hydrologic behavior of catchment using similar environment data is a rule rather than exception. The Consulting Engineer during the feasibility studies correlated the rainfall data from stations of similar environment that existed in different regions of Oman for the estimation of the catchment rainfall. The records of rainfall for station at Tahwah indicate that majority, of rain in a year falls in small number of relatively heavy storms over this catchment. Considering it as representative, its correlation with the data of Muscat station yielded a value of 140 mm as the representative long term annual average rainfall of the Wadi Fulayj catchment. The rainfall in the catchment varies with elevation and influenced by the proximity of Tahwah range. Detailed evaluation during feasibility stage, found that for the purpose of estimation of runoff the average catchment rainfall for a large event could be considered as 0.84 times the Tahwah rainfall. Most of the rainfall occurs during the winter (primarily in February and March) due to depressions moving southward from the Mediterranean Sea, tracking roughly parallel with the Jabal Akhdar range in Oman. These events are generally larger in extent, longer in duration, but of lower intensity than summer convective storms. Summer rainfall is more sporadic more localized and depends on the location of inter-tropical convergence zone over the Arabian Peninsula. The past record shows 1983, 1986, and 1990 as wet years and 1984, 1985 and 1991 as dry years.

Flood Runoff

Wadi Fulayj is non perennial for its entire length. The main wadi channel is about 40 km long above the dam and 48 km upto the Gulf of Oman. Short duration flows occur during rain storm periods. A recording flow gauge was installed in November 1984 at Rafsah , (No. GV497380) a location few kilometers upstream from the recharge dam. The wadi channel here passes through the rocks with a catchment of 516 km^2. In this upper rocky catchment some 117 km^2 is occupied by alluvium covering the central part of valley with relatively flat slopes, where a part of surface runoff is intercepted in the storage, and the rest passes the gauging site. The Rafsah wadi gauge measures the majority of flow entering the reservoir area with the exception of inputs from wadi Misliq which joins wadi Al Fulayj between the wadi gauge and the reservoir area. On 17th March 1986 rainfall over the catchment resulted a flood with a peak discharge of 268 cubic meter per second at gauging station recording highest daily volume of 2 MCM. The analyses lead to an estimation of 35.4 mm catchment rainfall and surface runoff factor of 7.8% for this event. A similar analysis of flood data (1985-87) gave an overall value of 11.0% as surface runoff factor. The mean annual flow is estimated as 2.3 MCM. The feasibility study based on the flood records, estimated the occurrence of more than two flood events in the wadi in a hydrologic year on long term basis.

Floods at the Dam

Since the commissioning of dam the flood reaching at the dam site have been recorded through automatic recorder (Ott strip chart type) installed inside the reservoir. Table-1 shows the detailed record of different floods, as duration, peak discharge, total flood volumes, and the amount of water spilled over the dam, interpreted from the recovered stage hydrographs. The accuracy of flood analysis for each event from the synthesis of stage hydrograph is reasonable because of satisfactory performance of the recording unit. The flood records have been arranged for the hydrologic years from (1991-92) to (1994-95). The total flood volume during the hydrologic year (1991-92) were 13.6 MCM with flood events spread in the month of February, March, April and May. Largest being in April over 10 MCM resulting from widespread rainfall over the catchment in successive events. Probably higher intensity, wide widespread rainfall resulted in torrential runoff, about 9.5 MCM (71%) flood of the event spilled over the dam crest. The floods during the hydrologic year 1992-93 occurred in the months of March and April in four events with a total amount of 5.35 MCM with a maximum size of 2.43 MCM on 12th April 1993 of which 1.75 MCM spilled over the dam crest. During the hydrologic years (1993-94), (1994-95) the total flood reaching the wadi Al Fulayj dam were 4.4 and 6.2 MCM of which 1.8 (41%) and 3.1 (49%) MCM spilled over the dam respectively. April is the month that records the large events for both the years with flood volumes 2.1 and 2.8 MCM respectively. During the first four years of operation of the Wadi Al Fulayj dam, there were eighteen main flood events out of which eight events had larger flood sizes than the capacity (0.78 MCM) of the dam. The excess water spilled over the dam and resulted in filling of the lagoon areas at the coast and runoff to the sea.

Hydrogeology

Aquifer Lithology and Distribution

The alluvium, downstream of the dam occupies the active wadi channel bounded by terrace deposits or sedimentary rocks and further down widen as a coastal plain with isolated outcrops of marly rocks. Detailed investigations involving test drilling, geophysical logging, geo-electrical surveys, infiltration tests and laboratory analyses of soil samples were carried out in the area from dam to Bilad As Sur gardens, to confirm the nature of alluvial deposits. These in general consist of silt, gravel with sand or clay sometimes cemented, as isolated lenses or layers of fair extension but of variable limited thickness, overlying the sedimentary bed rock. The gravel layers at few horizon show some degree of cementation. The thickness of gravel aquifer varies from few meters to over 30 meters, increasing towards downstream and generally encountered in the alluvium, which is usually shallow (average 45 m) overlying the bedrock. Generally the drilled wells have a finishing depth within 40 meters. The study of geologic logs indicate a change in lithology even for a short distance. The alluvial character differs near the coast where the coarser material of variable thickness between 10 to 40 meters is found to over lie the thick marly clays.

Table-1 **Recorded Floods at Wadi Al Fulayj [Sur] -Recharge Dam**

For Hydrological Years(91-92)-(94-95)

Hydrologic Year	Flood events	Max Reservoir Level (masl)	Discharges m³/s		Flood MCM	Volumes Spillover MCM	Rainfall Tahwah		Remarks
			Inflow	Spillway			Months	mm	
	11-2-92	18.58	341.4	12.66	1.3890	0.1802	2-92	39.80	
	23-3-92	18.46	155.6	0.00	0.8810	0.0000	3-92	14.00	
1991-1992	4-4-92	19.40	1491.1	605.77	8.3453	7.4970	4-92	65.52	
	6-4-92	18.70	56.3	54.89	2.1405	2.0578			
	7-5-92	18.48	96.0	0.00	0.8275	0.0000	5-92	3.80	
Total:					**13.5833**	**9.7350**			****157.40**
	1-3-93	18.47	126.4	0.00	0.7567	0.0000	3-93	61.80	
	28-3-93	18.27	137.7	0.00	1.0087	0.0000			
1992-1993	5-4-93	18.56	161.4	9.50	1.1462	0.3783	4-93	21.40	
	12-4-93	18.71	243.3	60.14	2.4389	1.7569			
Total:					**5.3505**	**2.1352**			**** 95.80**
	9-1-94	16.09	16.0	0.00	0.1200	0.0000	1-94	4.40	
1993-1994	12-4-94	18.68	197.1	47.01	2.1834	1.0364	4-94	23.40	
	8-5-94	18.64	575.0	31.45	1.6275	0.7947	5-94	5.60	
	5-8-94	17.56	170.0	0.00	0.4687	0.0000	8-94	9.00	
Total:					**4.3996**	**1.8311**			**** 46.40**
	16-11-94	16.58	324.6	12.66	1.0917	0.2348	11-94	0.60	
	6-1-95	17.00	13.4	0.00	0.3315	0.7670	1-95	0.80	
1994-1995	10-3-95	18.73	390.0	70.63	1.5876	2.0643	3-95	25.40	
	25-4-95	18.89	1045.0	164.13	2.8930	0.0000	4-95	15.00	
	22-7-95	17.11	14.7	0.00	0.3188		7-95	48.20	
Total:					**6.2226**	**3.0661**			**** 109.40**

*** Total Anual Rainfall at the station*

Aquifer Parameter and Groundwater Flow

Groundwater in the alluvial aquifers generally occurs under unconfined condition. However semi-unconfined condition is encountered at places where the aquifer is cemented. The depth to water below land surface near dam ranges from 7.2 m in well STW-2 to 12.5 m in well STW-4, during recharge period, and in dry season, the same drop to 16 and 18.8 m respectively. Further down, near the coast the water table is found between 2 to 4 meters below land surface.

The results of pumping tests/step tests on investigation wells indicate that the aquifer is fairly transmissive. Wells have specific capacity between 0.28 to 2.5 m3/min/m of drawdown. The results of analysis of aquifer tests show wide range in aquifer transmissivity. However, the appropriate values of transmissivity which seems to be in agreement with the type of lithology, is 15,000 M^2/day for coarse gravel aquifer to 7,000 M^2/day for gravel with clay or sand. The storage coefficient varies between 0.1 to 0.05. The results of field test on surface infiltration and other laboratory tests show that the wadi channel material have infiltration capacity between 1 to 3 meter/day. The hydraulic gradient is steeper in the narrow width of wadi and down in the plain it is relatively flat. The value of hydraulic gradient varies from 0.0025 to 0.0015. The subsurface flow that passes from the hard rock bounded wadi near Rafsah and enter the plain near the dam, may vary between 8,000 to 5,000 M^3/day, respectively during high and low water table periods.

Water Quality and Seawater Intrusion

The groundwater in the area from the dam to downstream up to Well No. STW-5 has an electrical conductivity value between 600 to 1200 μmhos/cm. Further down in the area the groundwater is the highly saline. Few selected dug well located in the irrigated area are under monitoring which show fluctuation in salinity of groundwater with time. The fluctuation in the salinity of groundwater from these wells is due to the one or combined effects of the following factors:

- Poor recharge from catchment due to dry spell at certain time resulting in to an inland shifting of sea water interface, which lies at shallow depth.
- Localized upconing of salt water in the well due to overpumping at times of peak requirement.
- Recharge from the catchment rainfall in a wet year resulting in to replenishment of quality of water.

Since the peak crop water demand during (April to August) is entirely dependent on groundwater, overpumping in summer deteriorates the quality of ground water in dug wells under use. In general the area prone to deterioration in water quality lies downstream to well No. STW-7. The monitoring data shows that the water quality fluctuation in dug wells is also influenced by individual well depth and water abstraction schedule.

The probable position of the interface (Figure 2) in the wadi near the coast has been prepared with the help of water table altitude records of (1994) using the Ghyben Herberz rule. The records of water levels of monitoring well STW-5 indicate that in dry period, before the construction of dam, the water level showed an altitude of a meter or so below sea level and in a recharge event rises from 3 to 7 meters above sea level. The quality of water in this well remains within a conductivity value of 1200 μmhos/cm. in either case. Whereas highly saline water is encountered at depth in wells No. STW-7 & 8 located further downstream. This indicates the inland extent of sea intrusion and the toe of interface at present stage somewhere at a location between wells No. STW5 & 7. It could be inferred that the transition zone lies beneath the irrigated lands and any increase in salinity of water is from mixing of more saline water at any time due water abstraction.

THE IMPACT OF RECHARGE DAM

Syntheses of Data

Detailed evaluation of artificial recharge and determination of water balances after the dam operation period is beyond the scope of present work. However, through the analysis of dam monitoring data, since it came under operation, and in conjunction with update knowledge on hydrogeology, the changes in ground water regime has been interpreted. A comparison to the observed conditions with the dam is drawn with, both to the period without dam and to what envisaged in the feasibility studies, towards the impact of the dam in the target areas. Data from regular periodic observations of an established monitoring network provide a basis of preliminary analysis. This includes monthly measurements on; water levels from 21 drilled wells, electrical conductivity of water samples from 10 selected open dug wells. Dam reservoir flow gauge records for each flood events provide, access to quantify inflows and outflow.

Flood Pattern & Review of Reservoir Size.

Due to the variation in the annual rainfall and its pattern the size and the numbers of flood reaching the dam is irregular during individual year. On the basis of early records the mean annual flow at wadi Rafsah is 2.3 MCM with a highest annual of 5.6 MCM in the year 1990. The years 1986-88 were relatively dry with no major flood event.

Table-1 shows the events and recorded sizes of the flood at the dam for the hydrologic years 1991-92 to 1994-95 and discussed under section 3 2.2. In each year floods occurred in four or five events with two or more of size larger than reservoir capacity resulting in over spilling. The floods of April 92 and April 95 record the maximum peak inflow of 1490 & 1050 m3/s. respectively at the dam. On the basis of Ministry of Water Resource's Flood Frequency Curve for Oman (1991), for catchment 670 km2 (dam site), the event could be regarded as 1 in ten year return period. Such an evaluation could deviate to lower side for a catchment like Wadi Al Fulayj due to its geographic location and circular to oval shape, that does not corresponds to other typical coastal catchment of Oman. Two to three events with larger flood size than the reservoir size are common in each recorded year. With its outlet closed the dam also served to cut the peak of flood and spilled volumes partly contribute as early stage recharge in the target area and the rest reach to the sea.

The flood records indicate the reservoir size (dam height) smaller than flood size of 1 in 5 return period. This however does not reflect the dam as under-designed, when, other deciding factors like, recovery and storage capacity of the aquifer, engineering solution and capital cost for a larger structure and potential threat to the safety of downstream areas, in case of dam failure, are considered.

Groundwater Recharge

Groundwater is abstracted from production wells installed in the wadi just downstream of dam, however the main target area is about 3 km from the dam. Recharge to groundwater from the dam occurs as infiltration from reservoir storage, as well as from the flood wetted area in the wadi and due to the increment in subsurface flow, from the dam for a time till a hydraulic head exists. During the flood periods the dam outlet is kept fully or partially closed with a purpose to increase the infiltration time, in the wadi course, particularly when its rate decreases due to initial saturation of the surface with early spilled water from the dam in the event of large flood. The stage hydrograph of the different flood events show that at the end of event the reservoir volume infiltrated in 4 to 10 days time, therefore the evaporation losses are small. The amount of recharge is dependent upon the number of time the dam is flooded and the duration of inflow of an ndividual event in a particular year.

Fluctuation of Water Levels

The locations of monitoring network is shown in Figure 3. Wells monthly monitored for water levels include from No. STW-1 to STW-5 and each well has two observation wells at the same location. Until recently 6 more wells are drilled and included in network and monitored since 95 onward. Figure-5

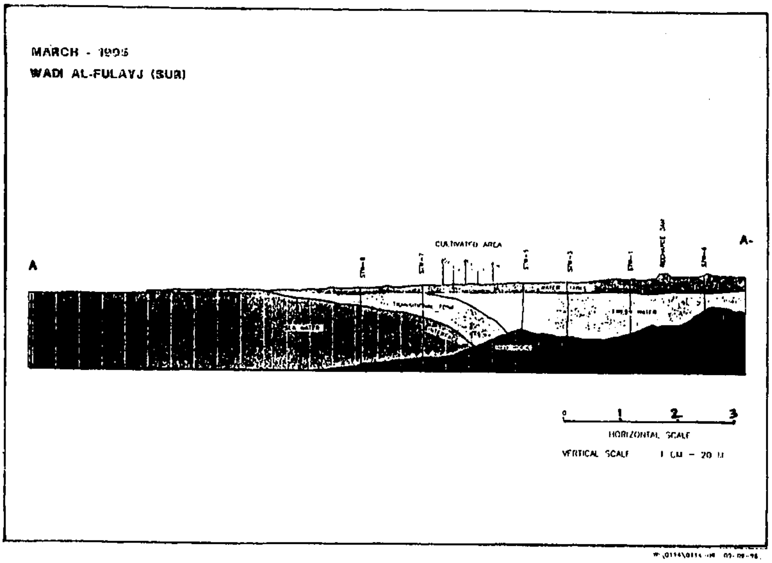

Figure -2. The Probable Position of Freshwater-Saltwater Interface

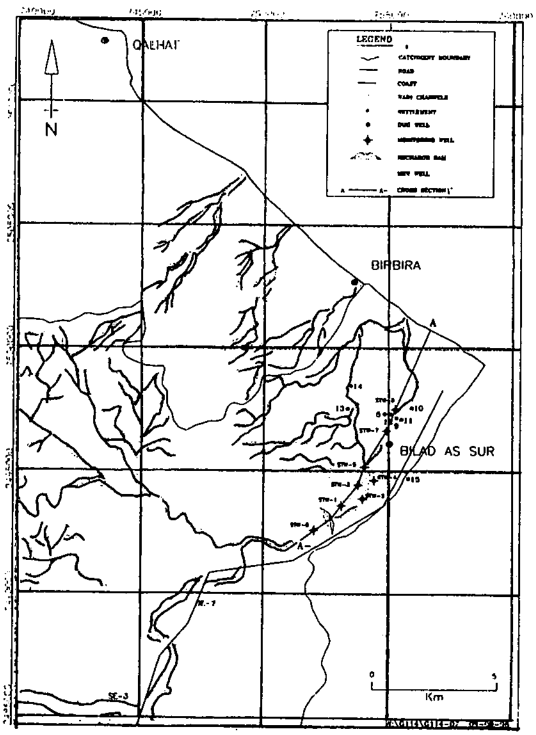

Figure -3. Location of Monitoring Well - Dug Well - Recharge Dam in Wadi Al Fulayj

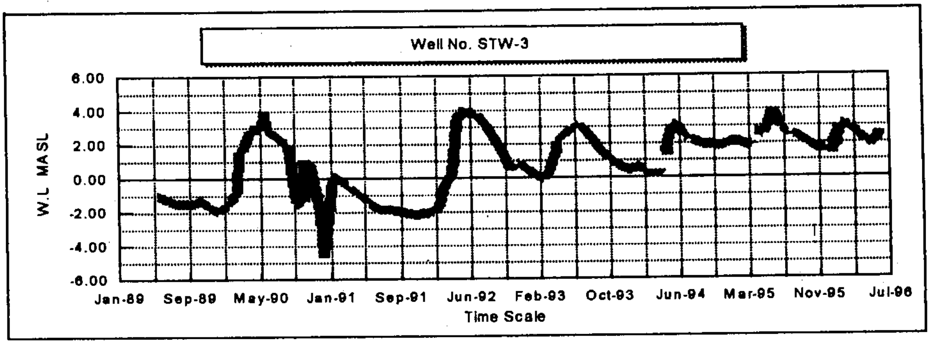

Figure -4. Well Hydrograph at Al Fulayj Recharge Dam -Sur

represents the water level hydrographs for the monitored wells up to year 1995. All the observed wells indicate quick response of rise of water level for each flood event. For the floods of April 1993 the rise or the recovery varied from over 7 meter in Well No. STW-1 close to the dam to 4 meters in Well No. STW-5 the furthermost away. Since the aquifers are unconfined the rise at a time correspond to the increase to the storage as recharge. This is further substantiated by smooth decay of ground water rise in all the wells at the same pattern and time in the hydrographs. The hydrographs show that the water level in wells does not decline to its initial level and a small rise persist in all the wells between the time lag of successive floods. This is probably due to the sustained subsurface flow contributed from upper alluvial section upstream of Rafsha, to the area. The recharge that could be beneficial to the irrigated land occurs in the area between Bilad As Sur gardens and the dam (about 6 km2), as elsewhere further down it could be non-recoverable due to mixing with saline body. Considering an average rise of 4.5 m during the year in an area of 6 km^2 with storage coefficient of 0.15 of the aquifer the recharge from the dam is about 2.7 MCM during each hydrological year.

Effects on Water Quality

Groundwater quality is monitored on (routine & flood monitoring) basis as field conductivity measurements of water samples from drilled observation wells, in addition to 6 selected dug wells in the target area. The water quality is fresh up to the location of well STW-5. However, further down where ground water salinity in general increases, the effects of recharge in quality improvement tends to be slow and progressive. Due to the presence of underlying saline water the quality of water from these wells fluctuate in response to factors, as over pumping and the occurrence of dry and recharge events. In some wells continuous deterioration in quality has occurred due to indiscriminate pumping. Generally the water has the conductivity more than 10,000 μmhos/cm. Whereas, in times onward to dam operation the water quality from the drilled Well Nos. STW-1 to STW-5 remains within a value of 1200 μmhos/cm, however in the main target area the response in quality improvement of water from under operation dug wells is slow. Being close to the sea most of the dug wells, tap water from the transitional quality zone, hence water quality changes are not very distinct. The changes are more responsive to closing and operation times and required yields from individual well. The records show quality fluctuation from a value from 28,000 to 11,000 μmhos/cm for water sample from Well No. 8. after floods in the dam. This trend is found in other wells (Figure . Since dispersion process in changing the quality of water is slow, a global effect of quality improvement may take some time span, as well as a need of sound management practice. The monitoring of five recently drilled Well Nos. STW-7 to STW-11 with screens placed in fresh and saline zones would provide a mean to evaluate the long term impact of the dam on water quality.

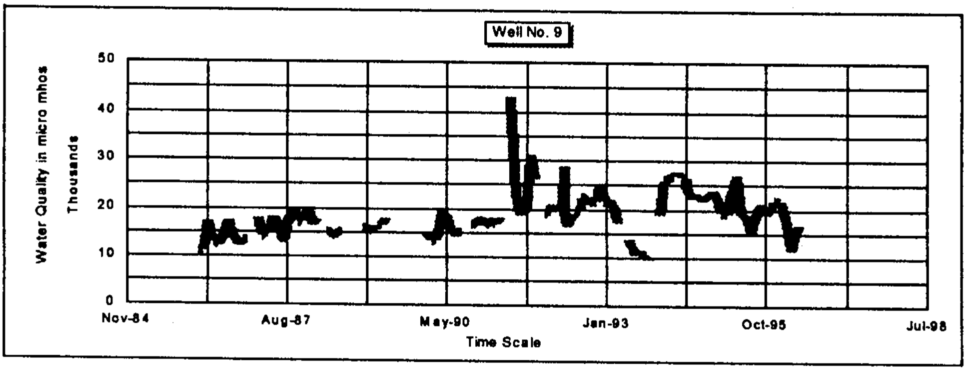

Figure -5. Water Quality Graph at Al Fulayj Recharge Dam - Sur

Groundwater Balance

A water balance study is beyond the scope and the purpose of this work, a general assessment of the present available potential (including artificial recharge) and groundwater use in the target area, has been made taking into consideration the previous estimates. The feasibility study (1986) assessed that total water requirement of the area were about 7.2 MCM against an estimated average annual potential of 1.5 MCM from wadi (without dam) and 2.6 MCM subsurface flow from the upper basin. The estimated deficit in the system were 3.1 MCM. Recent estimates of agriculture areas from the map sheet 1: 100,000 identified, a total of 375 hectares palmeries with majority (285 hectares) in the Bilad As Sur. Consumptive use for the target area (285 hectares) at the rate 2/m/ha/year could be estimated as 5.7 MCM. Groundwater abstraction form well field (located downstream to dam) for domestic use were estimated about 2.0 MCM / year.

For the observed years the annual recharge as flood infiltration from the dam, effective to the target area could be averaged as 2.8 MCM, over and above the estimated natural (1.5 MCM) recharge without dam. Recharge as sub-surface flow contribution from the upper catchment is estimated on an average 3.0 MCM, based on hydraulic gradient and section lithology of wadi near the dam. Therefore average annual potential of the target area since the dam came in to operation is of the order of 7.3 MCM. The groundwater use is approximately 7.7 MCM. This indicate somewhat balancing state during the observed hydrologic years and satisfactory contribution from the dam. These estimates are preliminary and subject to further revision.

CONCLUSION

Since February 1992 when the wadi Al Fulayj Recharge Dam started operation, there were over 18 flood events recorded at the dam up to the end of hydrologic year 1994-95. In each hydrologic year there were 4 to 5 flood events filling the dam and the year 1991-92 recorded maximum total of 13.5 MCM. For the remaining years the total flood volume ranged between 4.4 and 6.2 MCM. A pattern common to each year is the occurrence of flood in the month of March and April, generally of large size than the retention capacity of the dam, a substantial part of the flood for these events spills over. The volume spilled over the dam were 7.5 & 2.0 MCM respectively for the flood events of April 92 and 95 which, with a little contribution to natural recharge spread in the coastal lagoon or went to sea.

The water retained in the dam for each event infiltrated and effectively recharged the aquifers in the area under exploitation. A sustained recovery in water level and improvement in the quality in the irrigated area has been monitored. Preliminary evaluation of the data indicate the contribution of recharge of the order of 2.7 MCM for each year over and above the natural recharge, within the groundwater exploited area. However the present level of groundwater exploitation and available potential including dam contribution during the year appears to be just in a balancing state. With the future increasing demands, additional recharge through some improvement works would be needed.

The aquifer in the area is shallow, with limited thickness hence with small storage capacity and in contact with saline water. Even with the dam, in a dry year there could be adverse effects, when the water is drawn from the storage. An integrated management program for water development is therefore recommended.

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Constraints in Traditional Hydrological Frequency Analysis Methods When Applied to Oman

Aisha Al Qurashi, Frederiek Kaul and Theodore Calma

CONSTRAINTS IN TRADITIONAL HYDROLOGICAL FREQUENCY ANALYSIS METHODS WHEN APPLIED TO OMAN

Aisha Al Qurashi, Frederick Kaul and Theodore Calma
Hydrology Data Analysis Section, Surface Water Department
Ministry of Water Resources, Sultanate of Oman

ABSTRACT

The paper is based on experience in Oman in flood, flow and rainfall frequency analysis. Certain traditional approaches have been found inapplicable directly for this arid region, and modifications have been needed to achieve realistic results.

A particular problem is that, apart from the khareef in Dhofar in the south, there is no regular wet season, and the rainfall is so erratic that droughts without effective rainfall can last for several years. The few storm and flood events which do occur tend to come in clusters. Sometimes there is less than one event per year on average in a data series. In these circumstances, an annual mean is not very meaningful, and even a peak-over-threshold approach is not straightforward. Handling rare cyclone events in coastal regions, especially where quantified observation periods are short, also poses problems.

The paper discusses the difficulties encountered, and describes ways found for overcoming them. It presents a brief summary of flood and rainfall frequencies as computed for Omani gauging stations with sufficient years of data for analysis. A comparison is made with the frequencies derived for other parts of the Arabian Peninsular.

Keywords: Oman, flood frequencies, rainfall frequencies, arid frequency methods.

INTRODUCTION

In the past year, a programme of frequency analyses has been embarked upon in the Sultanate's Ministry of Water Resources, involving hourly, daily, monthly and annual rainfall, and flood peak flows and monthly flood volumes.

In theory, for nearly all stations, there are not yet sufficient years of data to estimate reliable frequencies. However, rapid development of the Sultanate is proceeding apace, and it cannot await the time when theoretically sufficient data are available. Hence best estimates are needed now as design parameters. Experience has shown that leaving this matter to design consultants is undesirable, resulting in differing approaches, and analyses of just a few stations local to the proposed project. It is clearly better to carry out regional or nation-wide analyses, using consistent methodology and assumptions, and making use so far as possible of cumulative experience at as many stations as possible.

Like virtually all of the Arabian Peninsular, the Sultanate of Oman (Figure 1) has a distinctly arid climate. Average annual rainfall ranges from 50 mm to 350 mm, and over the nation as a whole it is about 100 mm. There is no wet or dry season, except in a small area of the Sultanate's southern tip at Salalah, where the khareef monsoon brings a very localised 3-month wet period from June to August. For most of the Sultanate, there can occasionally be periods of a year or more with no rainfall at all, and from an agricultural point of view, no effective rainfall at all can be relied upon at any time of the year to sustain crop growth. A more detailed description of Oman's hydrological characteristics is presented in Ref [1].

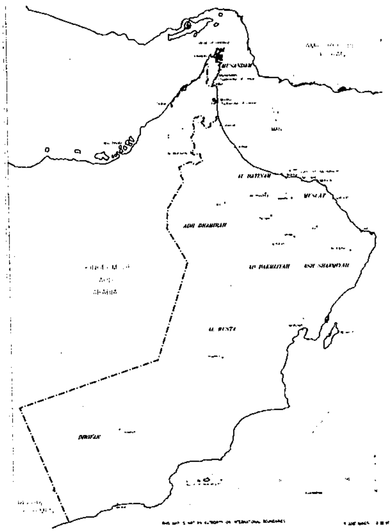

Fig. 1. Administrative Regions in the Sultanate of Oman

The special circumstances of arid hydrology seem to feature too little in the traditional hydrological text books. The nature of the data for an arid region such as Oman often do not conform to traditionally taught methods, and modifications and compromises are needed in practice, and also the requirement to demonstrate why text book approaches are less suitable or even inapplicable.

Several regional characteristics were found to be critical:

(a) As in any arid region, storm and flood events are rare in Oman, quite a large proportion of years having no significant event. The definition of what is a flood and what is a minor flow can be a problem. Annual series may often not be appropriate for these short duration events, and peak-over-threshold series better.

(b) Storm and flood events often occur in clusters of two, three or more days. There are also periods when there appear to be groups of clusters occurring over a period of weeks or months, and not particularly related to any long term cyclicity due to sunspot activity, etc., but resulting in exceptionally wet years.

(c) The station-year approach is useful where, as for Oman, the data period is very short. However, in Oman, occasional heavy storms which bring about most of the usable recharge and largest floods tend to be widespread events covering most of the north or south of the country. Hence it is not reasonable to assume that flood and storm events are independent events at each hydrometric station, and this largely precludes use of the station-year approach.

(d) For arid regions, where storm and flood events are rare and where 90% or more of the time it is dry, it is particularly important to have long record periods to establish flood and storm characteristics. A few occasional severe storm events or unusual droughts can greatly bias estimates of averages or frequency plot slopes, and simulation of water resources projects over a biased series of years leads to wrong project expectations. Flow data periods for Omani stations are very short, typically 15 years or less for wadi gauges, and 20 years or less for rainfall stations.

(e) Wadi flood peak flow estimates are particularly difficult to estimate with a high degree of accuracy. Flashiness, high flow velocities, and access difficulties in terms of flooded roads, remote locations and timeliness, all contribute to this difficulty. Hence indirect measurements must be resorted to, but at the expense of precision.

(f) In most parts of the world, area relates relatively well with flood peak frequencies. However, in arid regions such as Oman, a flood peak flow rate depends more on where it is measured. Floods tend to be high within the mountains, where higher rainfall, bare rock, narrow gorges and little alluvium tend to prevail. When the runoff from the mountains hits the alluvial plains of the coast or interior, the floods spread out and infiltrate, and it is common for a large flood at the foot of the mountain to become small or non-existent further downstream.

(g) Oman has several distinctly differing weather influences affecting storm rainfall:

- cyclones along the coastal regions and in the flatter Interior
- khareef monsoon effects in the south around Salalah, but also affecting to a lesser extent the Interior
- more typical frontal winter and convective summer storms, affecting particularly northern regions

Although it is sometimes possible to ascertain the storm type, this is generally difficult. Furthermore, to analyse separately storm rainfalls associated with the different storm types requires many years of data to have enough of each storm type, and such long series are available at only 3, far from typical locations, Muscat, Salalah and Masirah Island.

An example of the difficulties involved in assessing accurate frequencies in such circumstances is demonstrated in Figure 2, which shows a Gumbel plot of the 67 annual maximum daily rainfalls on record since 1895 for Muscat rainfall station. For these Muscat data, the plot does not look unreasonable (though Gumbel was shown to fit poorly for most Omani stations). However, in the famous June 1890 cyclone, the daily total rainfall measured at Muscat was 286 mm, which, by extrapolation on Figure 2, would have an impossibly long return period of more than 11 million years! Bearing in mind that a 1-day total of 424 mm rainfall was recorded in Masirah station in another cyclone in 1977, it seems unlikely that these events are rarer than 100 or 200 year events, but any standard method of analysis results in a very much longer return period. This example underlines the dangers of over-reliance on purely statistical analyses, and the importance of humility in interpreting the results of such hydrological analyses.

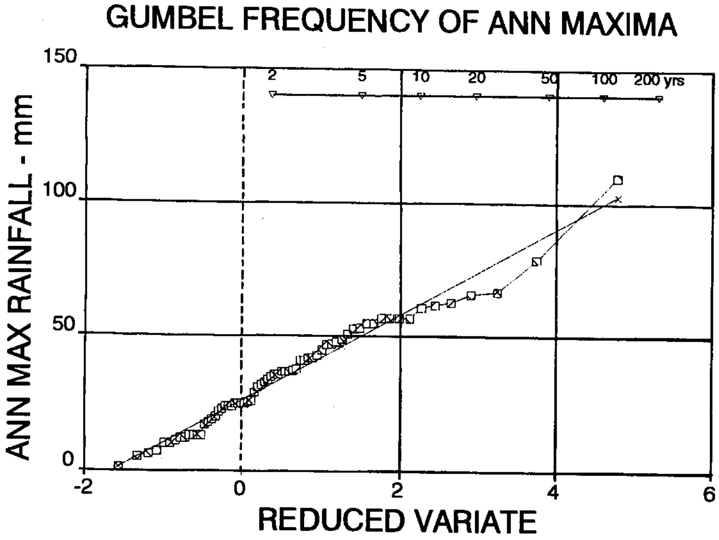

Fig. 2. Muscat Maximum 1-Day Rainfall Frequencies

FLOOD PEAK FREQUENCIES

Flood peak frequencies were computed for the 50 wadi gauging stations with sufficient years of data out of a total of 140, the criterion in this case being that they must have at least 12 years of systematic records. This excluded one-off estimates for severe historic flood events, although these were included in analyses. There are no data for Al Wusta, the central desert.

To demonstrate the validity of different approaches, 3 standard methods and variations of them were tested to analyse data for all stations. The first involved peak-over-threshold (POT), or partial series data, with log return period plotting, using the same number of events as years of data [2]. Annual series were used with log-Pearson III and Gumbel methods. It was found that the large number of zero or near zero events, particularly in the annual series, had to be discarded from best line-fitting. One of the objectives of the exercise was to attempt to assess regional flood characteristics throughout Oman, making a standardised approach desirable. In the latter context, it was found that best line-fitting from the 50% point upwards was generally appropriate. In the case of the POT analysis, straight line fitting was shown to be suitable in general, and this avoided too much emphasis on individual highest events which curve-fitting would introduce. A comparison of results showed that in effectively all cases, the POT approach

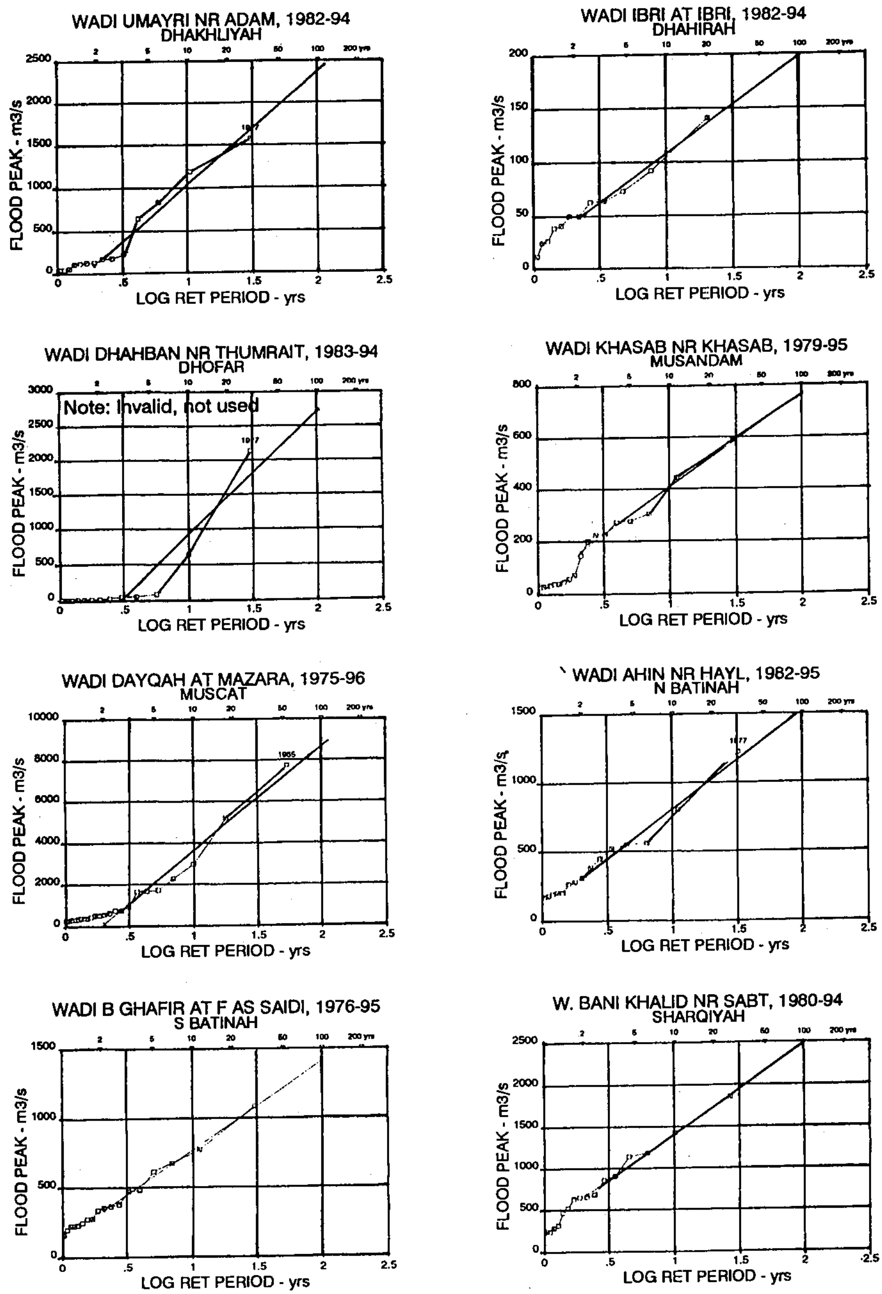

FIGURE 3 Flood Peak Frequency Plots

produced the best line-fitting, particularly in the higher range which is the area of interest for flood frequency analysis. This was only partly due to the greater number of events to define the slope of the line for these short data series, but partly due to log-Pearson III's emphasis on curve-fitting to the lowest points, which led to poor fitting for upper points, even when the lowest 50% of points had been discarded.

Figure 3 shows the POT frequency plots for a selection of wadi stations, involving one for each Region. They include years of estimated historic severe events when these occurred before stations were installed and records began. Frequencies for all usable data sets are shown in **Table 1**, involving 33 stations with catchment areas from 59 km² to 2,137 km², and data periods up to 23 years (W Dayqah). Hence frequencies beyond 50 years are only very generally indicative. For some stations, data series showed only 2 or 3 real flood events, the remainder being much lower and almost zero. In such cases, sometimes involving only 12 years of data, it was concluded that frequencies could not be realistically computed until more years of data had been collected. The latter applied to 17 of the 50 wadi gauging stations, including all stations in Dhofar, and so the listed frequencies apply only to Northern Oman; the problem is demonstrated for a Dhofar station, Wadi Dhahban near Thumrait, in Figure 3. It can also be seen from Figure 3 that the points below 50% are sometimes convex and sometimes concave relative to the upper points.

TABLE 1
FLOOD PEAK FREQUENCIES FOR ALL REGIONS IN ORDER OF CATCHMENT AREAS
POT Frequency Analysis (Partial Series)

Station	Wadi	Area	Period of Record	Upstream Alluvium	Return Period: Mean	5	10	20	50	100-yrs	World Max
		km²		**	Return Period floods - m³/s						m³/s
Al Hamra	Misfah	59	1981-94	Low	127	270	366	462	589	685	3224
Limah	Nataba	60	1981-94	Medium	63	139	251	364	513	626	3245
Sharm	Sharm	204	1982-94	Low	205	394	602	811	1087	1295	5295
Fujayl	Sarami	212	1981-94	Low	136	325	555	786	1091	1321	5377
Salhad	Al Bih	222	1979-94	High	78	157	205	254	318	366	5477
Sabakh	Fizh	266	1981-94	Low	109	253	368	483	634	749	5888
Qalhat	Hilm	289	1981-95	Medium	215	512	724	936	1216	1428	6086
Khasab	Khasab	299	1975-94	High	147	306	415	524	668	777	6170
Dibab	Arabiyin	307	1981-94	Low	182	417	549	681	855	987	6235
Nizwa	Al Abyadh	346	1977-95	Low	335	691	1175	1658	2297	2781	6541
Samad	Samad	351	1981-95	Medium	194	489	835	1181	1639	1985	6578
Uwaydat	Diyan	361	1980-94	High	23	43	61	79	102	120	6653
Sabt	B. Khalid	368	1977-94	Low	602	1092	1420	1748	2181	2509	6704
Ghuzayn	Hawasinah	387	1981-94	Low	192	418	718	1018	1414	1714	6840
Ajib	Hatta	437	1976-95	Low	364	634	904	1173	1530	1799	7181
Yanqul	Yanqul	472	1980-94	Medium	203	435	781	1127	1584	1930	7406
Sur	Rafsah	516	1980-94	Medium	157	316	425	534	678	787	7675
F as Saidi	B Ghafir	602	1976-95	Low	299	579	772	964	1219	1411	8163
Mulayinah	Al Jizi	630	1979-95	Low	275	494	643	792	989	1138	8313
Mazahit	Far	687	1980-94	Medium	352	658	909	1161	1493	1744	8606
Hayl	Ahin	734	1982-94	Low	331	614	826	1038	1318	1530	8836
Hajar	Al Abyadh	751	1983-95	Medium	334	595	768	941	1169	1341	8918
Al Abyadh	Al Abyadh	763	1981-95	Medium	297	563	741	919	1155	1334	8974
Khaburah	Hawasinah	878	1982-94	High	68	125	189	254	338	403	9493
Ibri	Ibri	893	1982-94	High	42	81	108	135	171	199	9557
Suwayq	B Ghafir	952	1977-94	High	57	111	182	252	345	416	9805
Adam 2	Adam	964	1982-94	High	82	247	379	511	686	818	9854
Bu Abali	B Kharus	1112	1983-94	High	40	72	106	141	186	221	10434
Dank	Dank	1307	1980-94	Medium	371	780	1229	1679	2272	2722	11130
Al Khawd	Al Khawd	1657	1972-94	Medium	246	537	817	1098	1469	1749	12239
Mazara	Dayqah	1711	1975-96	Low	893	2115	3630	5145	7148	8664	12397
Sulayf	Lusayl	1789	1982-94	High	201	443	684	925	1244	1485	12620
Adam 1	Umayri	2137	1982-94	High	212	647	1045	1442	1968	2366	13549

Notes: 1. Data period is since station installation, and does not include historic flood estimates made at some stations and included in analyses.
2. Upstream alluvium relates to likely routing effect on floods, i.e. low alluvium upstream tends to lead to little routing effect or reduction of mountain flood peaks, whereas high alluvium tends to cause a large reduction in flood peaks.
3. Mean is mean of annual flood series, not POT series.

Included in **Table 1** are estimates of the mean annual flood (MAF). In arid regions, the MAF tends to be highly dependent on a few very high floods, and so accurate estimates of MAF can only be achieved after many years of data have been collected.

The effect of flood routing as floods pass from mountain gorges to cross the alluvial plains downstream is demonstrated in **Table 1** by the column indicating low, medium or high alluvium upstream. Where floods are confined to mountain gorges, such as Wadi Dayqah, flood peaks can be very large, but after passing across the Batinah plain, stations such as Uwaydat on Wadi Diyan show very low flood peak frequencies. Catchment steepness effects on flood peaks in Oman are currently being investigated.

One difficulty in using short flood data periods in arid regions is that a few large floods will tend dominate the upper end of a frequency plot, while the lower end may be made up of very small events often questionable as flood events at all. An apparently good apparent fit may by chance result, which may nevertheless be misleading. The lower points may be depressed unrealistically if they are not real floods, while the upper points, being very much higher, cause the best-fit line to be unduly steep, resulting in absurdly high predicted floods at small extrapolations. Hence a check that 100-year or 200-year predicted floods are within the likely realms of reality, e.g. not exceeding world maximum recorded floods (after Rodier [3], shown for comparison in **Table 1**), provides a useful check on the slope of the plot, despite such extrapolation being way beyond the valid extrapolation range for the data period.

It is notable that the average Omani flood frequency growth factors, based on the MAF estimates in **Table 1**, are close to those reported by Farquharson and others [4] for arid and semi-arid regions and Nouh [5] for south-west Saudi Arabia. The 50-year and 100-year floods, for example, are on average 5.6 and 6.7 times the MAF respectively, and they are much the same for categories of low and medium alluvium upstream, and even high.

However, the average MAF relationship to area quoted in [4] for arid regions:

$$\text{MAF (m}^3\text{/s)} = 2.05\ A^{0.571}\ (A = \text{area, in km}^2)$$

is clearly not applicable to Oman. Floods in Oman are highly affected by the degree of upstream alluvium, and there is little relationship between area and MAF for wadis where there is substantial alluvium upstream. However, for wadis shown in Table 1 as having low or medium alluvium upstream, there is a reasonable relationship, with r^2 of 0.54:

$$MAF\ (m^3/s) = 12.4\ A^{0.49}\ (A = \text{area, in } km^2).$$

This formula results in average MAFs which are 4 times as high as derived using the formula from Reference [4]. Omani floods therefore tend to be higher.

MONTHLY FLOOD VOLUME FREQUENCIES

A useful indicator in monitoring water resources is flood volume frequency. It is sometimes necessary to compare rarity of a flood event with its recharge effects or its operational effects on a water resources development. For this purpose, frequencies of 1-day, 1-month and annual runoff volumes are being assessed for selected wadi gauging stations throughout the Sultanate. **Figure 4** shows a sample of monthly flood volume frequencies, the method used being POT as described above. As for flood peaks, the flood volume plots show the lower end of the distribution as having little relevance to the upper end of the plots, and so, as for flood peaks, best line-fitting was carried out from the 50% point upwards.

DAILY AND MONTHLY MAXIMUM RAINFALL

Previous valuable work on storm rainfall analysis in Oman was carried out by Wheater [6], based on a severe storm of May 1981 in the Capital Area. The present programme of frequency analyses will update and extend that work on a national basis.

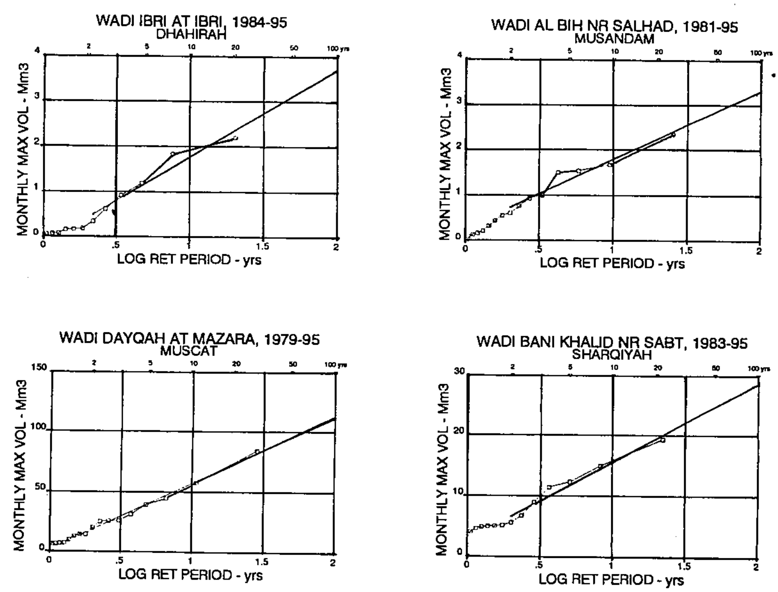

Fig. 4. Monthly Flood Volume Frequency Plots

Frequency analyses of maximum daily and monthly rainfalls have been carried out using the POT method described above for flood peaks, except that in this case, all points (not just above the 50% rank) were used in best line-fitting. All rainfall stations with more than 15 years of data were used in this exercise, a few manual stations being rejected after data quality checks. In all, 44 rainfall stations out of the Sultanate's 300 station network were available for this analysis. They included Muscat, with 100 years of monthly data, and Salalah and Masirah Island, both with about 50 years of data.

Frequency results and plots for one station per Region are shown in **Table 2** and **Figure 5** (1-day and 1-month only). They involve a mixture of inland and coastal stations, for a range of elevations up to nearly 2,000 m above sea level (Saiq). They are shown for return periods up to 100-years, but in most cases, beyond 50 years should be regarded as no more than generally indicative.

The simple approach was taken of assembling for analysis the data series of all recorded maximum totals for 1-day, 2-day, 3-day, 1-month and 2-month rainfalls, again the number of peak values selected being the same as the number of years of data. The problem of clusters soon became apparent. Storms often occurred in wet periods of several consecutive days, related to the same weather system, but rarely continuous for more than a few hours. The alternative approach of using only one event per cluster may be taken. However, since serious storm events are so rare in Oman, this approach results in the exclusion of many of the largest 1-day and 2-day events and the inclusion instead of a number of very small events. The latter has the effect described earlier of steepening the frequency plot, and causing even small extrapolations to be questionably high.

Clusters of wet days often involve 2 days and sometimes 3 days, but not frequently more. Hence 3-day totals are largely free of the cluster problem. However, a consequence of the relative rarity of storm events is that when 1-, 2-, and 3-day storm totals are analysed using the POT method with all daily events, after amalgamation of second and third rainfall days, there are sometimes insufficient events to ensure that the lower end of 2- and 3-day event plots are higher than the 1-day plot. The decreasing number of real events means that steepening of slopes of best-fit lines results, and discarding of lowest points before best line-fitting needs to be considered for rainfall, as well as flood frequency.

It was noted that straight-line fitting seemed generally appropriate for 1- to 3-day maximum rainfalls, but for longer durations of 1 or 2 months, signs of upward curving are apparent in some plots and may need to be accommodated by curve-fitting. However, at a few stations along the south or eastern coast, including Salalah (**Figure 5**), Masirah and Sur, even 1- to 3-day storm total

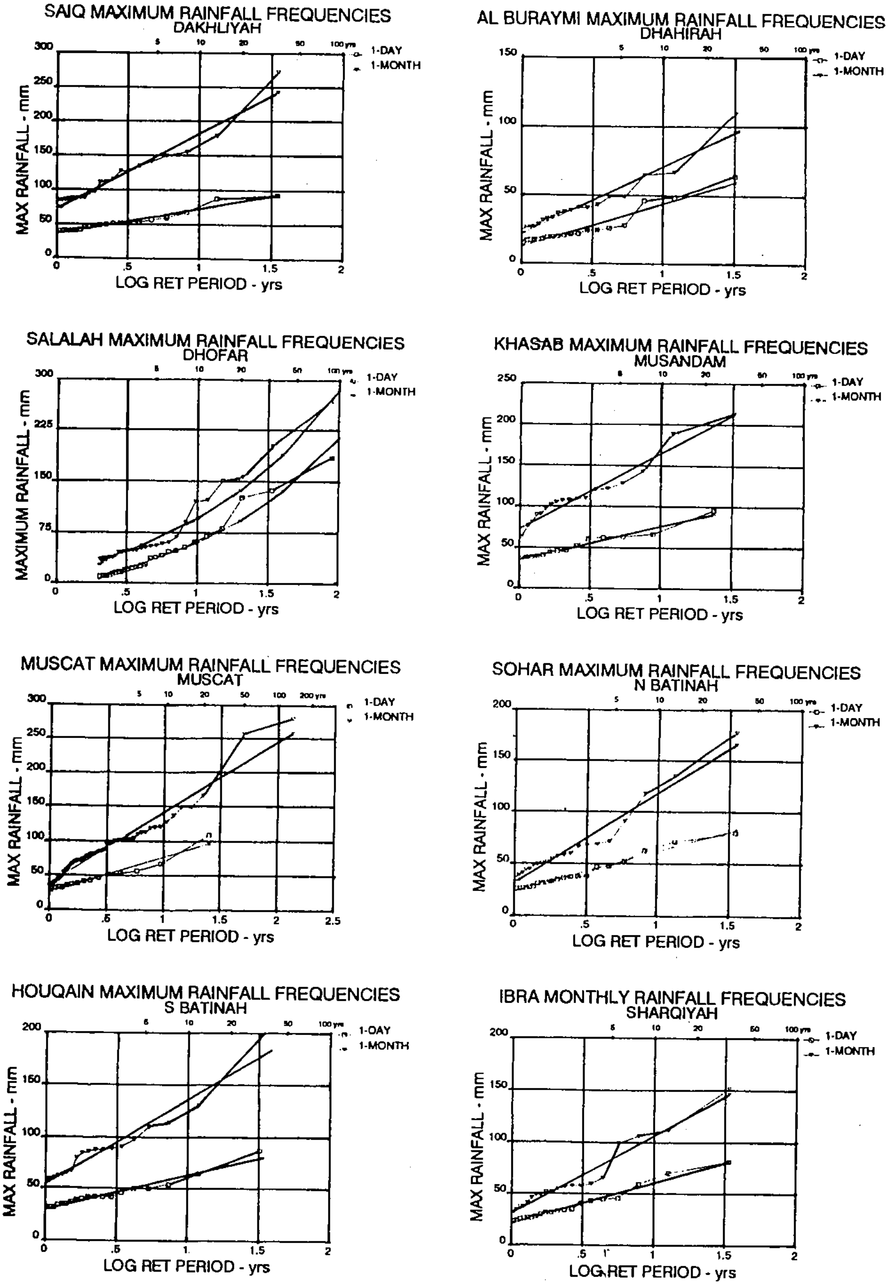

FIGURE 5 1-Day and 1-Month Maximum Rainfall Frequency Plots

plots showed distinct upward curvature. The rainfall at all of these latter locations is particularly influenced by occasional cyclones, which have much less effect on rainfall statistics for stations along the Batinah coast in the north, or for the interior beyond the mountains. For these stations, log-log plots with line-fitting from the 50% point upwards were slightly better, but still not ideal. A log Pearson III plot, again with line-fitting from the 50% point upwards, was marginally better. An example of this is shown in Figure 5 for Salalah, but it can be seen that the fit is still poor, particularly for the 1-month rainfalls. The poor fitting meant that 3-day and 1-month frequency best-fit lines crossed each other, and for this reason the 3-day values are not shown in Table 2. However, future attempts will be made to separate the different storm types for these and similar stations, so that very mixed statistical populations can be avoided.

TABLE 2

MAXIMUM DAILY AND MONTHLY RAINFALL FREQUENCIES

REGION	Station (Elevation)	Duration	Maximum Rainfall (mm) for Return Period: 5-yr	10-yr	20-yr	50-yr	100-yr
DAKHLIYAH	Saiq (1,950 m)	1-day	63	74	85	99	110
		3-day	92	110	128	152	170
		1-month	150	183	217	261	294
DHAHIRAH	Al Buraymi (299 m)	1-day	35	44	54	66	76
		3-day	43	53	64	78	88
		1-month	57	71	86	106	121
DHOFAR	Salalah (20 m)	1-day*	32	60	93	147	216
		3-day**	-	-	-	-	-
		1-month*	62	97	137	203	286
MUSANDAM	Khasab (3 m)	1-day	65	77	89	106	118
		3-day	84	101	119	142	159
		1-month	122	143	165	193	215
MUSCAT	Muscat (20 m)	1-day	62	77	92	112	127
		3-day	77	96	116	142	161
		1-month	88	110	131	160	182
N BATINAH	Sohar (15 m)	1-day	51	62	74	89	101
		3-day	69	88	107	132	151
		1-month	93	119	145	180	206
S BATINAH	Houqain (225 m)	1-day	53	64	74	87	97
		3-day	79	92	106	124	138
		1-month	112	136	161	193	218
SHARQIYAH	Ibra (425 m)	1-day	49	61	73	89	102
		3-day	65	83	101	125	143
		1-month	84	107	130	160	183

Notes: * POT used elsewhere in table not applicable to Salalah. Log Pearson III used for Salalah, but still poor fit
** 3-day and 1-month best fit lines for Salalah cross. Hence Salalah 3-day values excluded.

It is noticeable that the ratios of 10-, 50-, and 100-year daily rainfalls to the 5-year values are much the same as those reported by Wheater and others [7] for

South-West Saudi Arabia.

ANNUAL RAINFALL FREQUENCIES

In any project simulation of a proposed water resources development over a series of years of data, it is necessary to understand whether the data period contains exceptionally wet years or series of years, and also drought periods. For this reason, annual frequency analyses have been carried out for key rainfall stations throughout the Sultanate. This involved 49 of the Sultanate's 300 rainfall stations, after quality checking and gap-filling for a standard 21-year period 1975-95.

Several frequency methods were attempted to analyse annual maximum rainfalls, and the most appropriate was found to be the general extreme value approach (GEV). The Jenkinson method [8] of GEV estimation by sextiles was used on batches of data, except when the "r" factor was outside the range shown in Jenkinson's tables, for example for Salalah. For the long durations of a year or more, low points become less of a problem and all points can be fitted. Examples of annual maximum rainfall frequencies are shown in **Figure 6**, relating to 1- and 5-year totals for 4 typical stations. The resulting annual maximum frequencies are presented in **Table 3.**

TABLE 3
EXAMPLES OF ANNUAL MAXIMUM RAINFALL FREQUENCIES

REGION	Station (Elevation)	Duration	Maximum Rainfall (mm) for Return Period: Mean	5-yr	10-yr	20-yr	50-yr
DHAHIRAH	Ibri (330 m)	1-yr	103	156	217	287	398
		2-yr	203	290	374	459	578
		3-yr	297	412	491	562	648
		5-yr	485	581	613	635	653
MUSCAT	Muscat (20 m)	1-yr	101	146	188	229	286
		2-yr	200	269	324	375	440
		3-yr	300	388	446	497	554
		5-yr	499	613	676	726	779
N BATINAH	Sohar (15 m)	1-yr	98	151	194	237	294
		2-yr	200	283	332	371	413
		3-yr	296	402	458	504	553
		5-yr	489	544	619	708	852
SHARQIYAH	Ibra (425 m)	1-yr	146	205	262	322	407
		2-yr	284	354	421	490	586
		3-yr	413	497	573	651	757
		5-yr	664	771	809	835	858

When plotted as distribution curves, Omani annual rainfall distributions are shown to be somewhat different from the examples of rainfall plots for arid regions presented by Rodier [9], mainly for Northern Africa. The closest would be for Kidal in Mali, but with a steeper plot showing drier years to be closer to

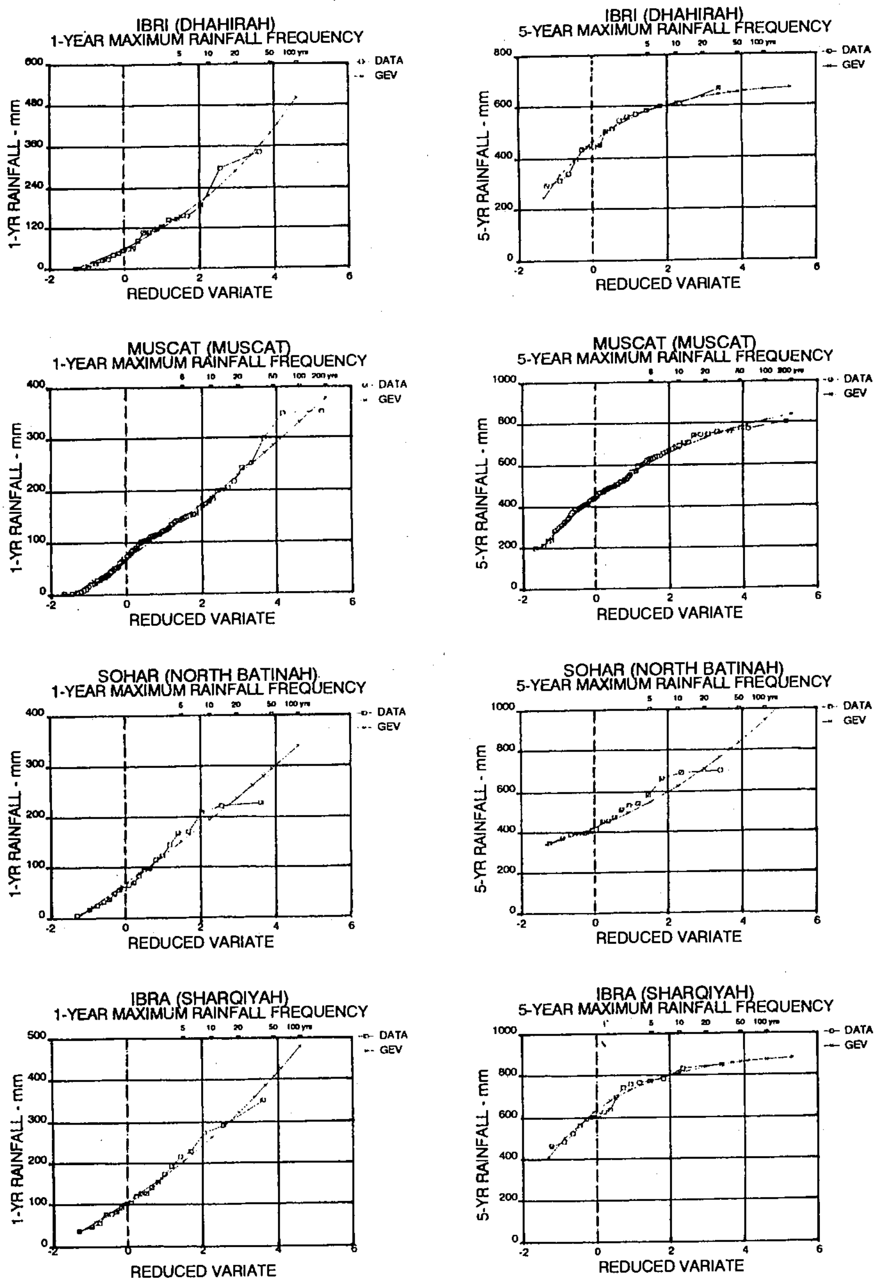

FIGURE 6 Annual Maximum Rainfall Frequency Plots

zero for Oman, reflecting the lack of a reliable wet season.
In the case of minimum annual rainfalls, standard approaches have proved difficult because the lower ends of plots are asymptotic to zero. In this case, a useful interim measure has been to use the 101-year Muscat record, which shows good correlation in annual rainfalls with most stations in northern Oman. By ranking minimum 1-year, 2-year, etc. rainfall totals for Muscat, approximate estimates can be made of the frequencies of droughts in recent years.

CONCLUSION

Flood and rainfall characteristics of Oman vary from north to south and from the cyclone-affected coast line to the interior, requiring differing analytical treatment. They are often not conducive to standard analyses such as log-Pearson III and Gumbel, and usually necessitate discarding a significant proportion of low points which tend to be zero or close to it. Floods may be infrequent, but when they do occur they can be severe, and although growth factors for Omani floods seem to conform reasonably with those in Saudi Arabia and Yemen, mean annual floods seem to be significantly higher in Oman. The effects of clusters needs careful interpretation, and work on this is continuing. As for any region for which data periods are short, care needs to be taken to investigate and take full account of all known severe historic events in the region. This is particularly so when rare cyclones can cause massive rainfall totals well beyond expectation based on analyses of data series made up of non-cyclone events.

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Investigations for Development of Groundwater Management Strategies in the Eastern Coastal Plain of the United Arab Emirates

Mohamed Sager Al-Assam and Wolfgang Wagner

INVESTIGATIONS FOR DEVELOPMENT OF GROUNDWATER MANAGEMENT STRATEGIES IN THE EASTERN COASTAL PLAIN OF THE UNITED ARAB EMIRATES

Mohamed Sager Al-Asam[1] & Wolfgang Wagner[2]
[1]Ministry of Agriculture and Fisheries
Dubai, UAE
[2]UN Economic and Social Commission for Western Asia
Amman, Jordan

ABSTRACT

The eastern coastal plains in the United Arab Emirates comprise productive sand and gravel aquifers and are among the few areas of the country where groundwater is replenished by present-day recharge. Intensive groundwater abstraction mainly for irrigation agriculture exceeds, however, by far the recharge and has created severe problems of salt water intrusion. To achieve a beneficial use of the limited fresh water resources, an efficient management of groundwater exploitation has to be introduced.

Investigation for the development of groundwater management strategies are described on the example of the Fujayarah coastal plain, where a wadi dam has been constructed for increase of groundwater recharge from flood flow infiltration. The investigations included groundwater flow simulations with a numerical model, and the following main conclusions were derived from the modeling results:

The wadi dam as an artificial recharge device and a well field situated 2 km. downstream of the dam provide an efficient set - up for management of the available fresh water resources.

Groundwater extraction further downstream in the wide coastal plain is highly endangered by sea water intrusion.

Improvement of the water quality and sustainable fresh water explotation may be achieved through a combination of technical measures, such as reduction of groundwater extraction near the coast, conveyance of water from upstream boreholes to irrigation areas, wider introduction of water saving irrigation methods, increased production of desalinated water for domestic supply.

THE NEED FOR GROUNDWATER MANAGEMENT IN THE EASTERN COASTAL PLAINS OF THE UAE

Along the eastern coast of the UAE, relatively narrow strips of coastal plains extend between the Oman Mountains and the Gulf of Oman in a stretch of approximately 70 km. length between Diba in the north and Khawr Kalba in the south (Fig. 1).

The Oman Mountains in the hinterland of the eastern coastal plains are composed of the Semail ophiolite complex, mainly basic igneous rocks and metamorphosed sedimentary rocks, which provides a fissure type aquifer with generally low productivity. The coastal plains comprise important aquifers composed of unconsolidated or semi - consolidated sands and gravels and are one of the few areas in the UAE where groundwater is replenished by present-day recharge from infiltration of rainfall or from flood flow in wadis, which enter the plains from the adjoining mountains. The coastal aquifers are intensively exploited, mainly for agricultural irrigation, through dug wells and drilled wells.

Favourable aquifer properties in some parts of the coastal plains permit the operation of wells with moderate to high yields, but recharge under the local climate conditions does not sustain intensive grounwater withdrawal. Average annual rainfall on the eastern coastal plain and its mountain hinterland ranges from 120 to 165 mm.For 1985, the deficit between present groundwater recharge and groundwater extraction was estimated at 62.2 million m^3/year for the eastern coastal area (IWACO 1986).

The intensive groundwater abstraction caused a wide-spread increase in water salinity, and abandoned irrigation wells and dying date plantations are obvious signs of the adverse effects of groundwater over-extraction. To achieve a beneficial use of the limited fresh water resources, an efficient management of groundwater exploitation has to be introduced, based on reliable figures of present groundwater replenishment.

Technical options for conservation or improvement of the groundwater quality in the eastern coastal plains are :

- Drastic reduction of groundwater extraction;
- Improvement of recharge through wadi dams;
- Optimization of groundwater abstraction near the coast;
- Built-up of hydraulic barriers near the coast, provided that a source for artificial water infiltration is available.

Tools for groundwater management to be developed in that connection may be :

- Assessment of the impact of recharge through wadi dams;
- Investigation of the position of the interface between fresh water and salt water or brackish water through geophysical methods;
- Hydraulic simulation modeling to define alternatives for optimizing groundwater extraction.

INVESTIGATION AREA WADI HAM

Investigations for the development of groundwater management are described on the example of the Fujayrah coastal plain, which constitutes the downstream section of Wadi Ham. Across that wadi, a dam has been constructed in 1983 at its exit from the mountains into the coastal plain with the aim of flood protection and increase of groundwater recharge.

The general hydrologic and groundwater conditions of the Wadi Ham caatchment can be described as follows:

The catchment of Wadi Ham at the dam site comprises 190 km^2. Long - term average surface runoff at the dam site is $5.35x10^6$ m^3/a. Groundwater flow in the ophiolite rocks and in wadi sediments in the catchment upstream of the dam may be in the order of $2x10^6$ m^3/a. About 75 % of the shallow groundwater flow in the upstream area is probably consumed for irrigation along wadis. Around $20x10^6$ m^3/a, more than 70% rainfall, are lost to evaporation.

The thickness of sand and gravel sediments, which constitute the main exploitable aquifer of the area, ranges from about 20 m. at the dam site to more than 100 m. near the coast. The sand and gravel aquifer extends over two sections:

- an about 2 km. wide and 3.5km. long section directly downstream of the dam with a saturated aquifer thickness of 10.40 m. a relatively steep gradient of the groundwater surface, transmissivities of <100 to around 200 m^3/day, low groundwater salinity.
- the coastal plain (4.5 km. length. widening to >8 km.) with a saturated aquifer thickness of generally >50 m. and up to > 90m. near the coast, low groundwater gradient, transmissivities of > 1000m^2/day, rapidly increasing groundwater salinity towards the coast.

Groundwater is exploited intensively from the sand and gravel aquifer for irrigation in the coastal plain between Fujayarh and Khawr Kalba. In 1985, groundwater extraction for irrigation in this area was in the order of $38x10^6 m^3$/ day year. Additionally, some well fields are operated for domestic supply. In the Shaara well field, situated 2 km. downstream of Wadi Ham dam in the wadi section of the aquifer, about 1 million m^3/year are extracted since 1988.

Groundwater level fluctuations have been monitored in a number of observation boreholes since 1987.

OCCURENCE OF FRESH WATER AND SALT WATER

Groundwater salinity distribution in the eastern region of the UAE shows the following pattern: Salinity is low to moderate in the fractured rocks of the Semail ophiolite formation and is generally moderate in the upper parts of the coastal plains. In the unconsolidated aquifers of the coastal plain, salinity generally increases in direction towards the sea, and brackish groundwater prevails in the plain along the sea coast. Groundwater with a salinity of >2g/l TDS extended to a distance of up to 4 km. from the sea coast in 1984 in the Fujayarh area (IWACO 1986). Since then, increase of water salinity has affected many irrigation wells and also boreholes of the Fujayarah water supply well field. In particular in the Kalba area south of Fujayarh city, high groundwater salinity is found in wells over wide parts of the coastal plain, and in considerable parts of the coastal aquifers, salt water certainly underlies the fresh or brackish water.

According to the hydrochemical composition of the groundwater, three main water types can be distinguished in the coastal plain and the adjoining ophiolite mountains:

a) fresh groundwater of Mg-HCO_3 or Mg - Cl type in the ophiolite complex,
b) fresh groundwater of Mg- Cl type in the upper parts of the coastal plains,
c) brackish to saline groundwater of Ca-Cl, Mg-Cl or Na- Cl type water in the coastal plains.

The dissolved constituents in fresh groundwater of the ophiolites can be attributed to atmospheric inputs with an enrichement of chloride and sulphate contents through evaporation and to silicate weathering processes in the zone or in the aaquifer reaction of soil CO_2 and water with silicate minerals.

Mean concentrations of major ions in fresh groundwater extracted in the upper part of the Fujayarh coastal plain are considerably higher than in the ophiolite groundwaters. Main sources of dissolved substances may be enrichment of Na. Cl and SO_4 in the infiltrating surface water through evaporative action and interaction of soil CO_2 with rock material: sands and gravels derived from Mg. rich rocks.

In the section of Wadi Ham directly downstream of the dam, the salinity of groundwater extracted from Shaara well field is low to moderate with TDS values between 350 and 900 mg./1. Fluctuations of groundwater salinity in boreholes of the well field are clearly related to recharge during flood events.

Salinity decreases sharply after rainfall in all observed boreholes of the well field but rises to previous levels of around 700mg/1 TDS within a few months. The observations reflect the dominant but brief impact of recharge through Wadi Ham dam on the groundwater regime in the wadi section. Recharge in the dam reservoir has an almost immediate effect on groundwater levels and groundwater salinity. After several weeks, conditions start to return to the pre - recharge state due to the movement of the recharge wave and to groundwater extraction in Shaara well field.

The available records indicate that the salinity increase of groundwater exploited by the well field, may, in general, remain at moderate salinity levels, up to about 1000mg/1 TDS.

A fresh water tongue extends within the coastal plain until about 6 km. downstream of the dam. The eastern end of the tongue apparently marks a rather sharp boundary between the extent of fresh water and brackish water.

Brackish Cl water extends over wide parts of the sand gravel aquifer of the Fujayarh coastal plain. Saline groundwater of Ca-Cl type with electrical conductivity values of 35 to 38 mS/cm was found in some deep investigation boreholes. The hydrochemical composition of brackish to saline groundwaters found in the Fujayarh coastal plain is characteristic for coastal sand aquifers with progressing sea water intrusion: when sea water with predominant Na and Cl ions intrudes a fresh water aquifer, Na is exchanged with Mg and Ca ions adsorbed on the surfaces of the aquifer material.

GROUNDWATER BEHAVIOUR UNDER ARTIFICIAL RECHARGE AND EXTRACTION CONDITIONS

One of the main technical options for conservation of water quality in aquifers of the coastal plain is the construction of wadi dams, through which infiltration of flood runoff into gravel and sand aquifers is enhanced. A quantitative analysis of the effects of recharge through a wadi dam was made for the Fujayarah coastal plain downstream of Wadi Ham dam with the help of a three-dimensional mathematical groundwater model. The main objectives of the construction of the model were:

- to simulate the development of flood flow, which is retained by Wadi Ham dam, into groundwater recharge and groundwater movement downstream of the dam.
- to develop concepts for the optimization of groundwater extraction downstream of the dam through simulation runs with the calibrated model.

The model of the Wadi Ham aquifers is based on the modeling code MODFLOW and comprises as area of 11km. x 10km. between Wadi Ham dam and the coast (Fig. 2). The area models is discretized into uniform grid of 200m. x 200 m. cells.

Date of the following parameters were used as input to the model:
- aquifer thickness, transmissivity, groundwater levels from 10 to 18 observation boreholes,
- monthly water level fluctuations in 11 observation wells over 5 to 7 years,
- hydrological data of flood events,
- assumed groundwater extraction rates,
- assumed values of groundwater inflow as subsurface flow in wadis.

In the model, the Wadi Ham aquifer is treated as an unconfined aquifer without hydraulic connection with the underlying ophiolites. Recharge to the alluvium is simulated as space and time dependent process, considering major rainfall events which occured in February 1990 and during several months in 1995 - 1996. Calibration runs were performed with the model as steady state calibration for initial groundwater head conditions in January 1990 and as transient (time dependent) calibrations for the period January 1990 to March 1996.

The model was used for prediction of the effects of groundwater abstraction in various scenarios:
- Comparing the effect of the recharge dam with natural recharge conditions, if the dam had not been constructed;
- Testing the effect of abandoning groundwater abstraction along the Fujayarah - Kalba coast and of reducing groundwater abstracton by 50%;
- Simulating the development of hypothetical new well fields in the coastal plain northwest or southwest of Fujayarah;
- Testing the effect of infiltration ponds along the coast.

The model simulation provided the following main results:

(a) The Wadi Ham ground water system appears to be very sensitive to (1) location of pumping site,(2) pumping rates and volumes from individual sites, and (3) conditions at the dam recharge site.

(b) The effect of the dam and its recharge reservoir is very beneficial. The Shaara well field depends on artificial recharge from the dam reservoir. Without the dam recharge, the Shaara well field would have to reduce its annual pumping by about 40%.

(c) The sea water intrusion can only be effectively dealt with by reducing the exploitation from the coastal plain. By eliminating theoretically any pumping from the plain, and restricting groundwater abstraction to the present extraction from Shaara well field, the ground water levels would recover everywhere to above the sea level in less than one year time. By reducing the pumping to about one half of the currently abstracted $6.2x10^6$ m^3/a, the levels would recover in the central part of the plain to above sea level in about one year time, and in the south near Kalba after three to four years.

(d) Simulation of recharge of 8,000 m^3/day into infiltration ponds near the coast during 60 to 90 days each year brings groundwater levels to above the sea level and fights back the sea water intrusion. However, these higher levels dissipate rather rapidly and in the rest of the year the levels are again controlled by the pumping along the caost.

(e) it is difficult to locate wells for additional abstraction. Simulating pumping from additional wells northwest or southwest of Fujayarah shows that a large depression of groundwater levels would be created, inviting sea water intrusion.

(f) It appears that the maximum development potential of the aquifer in the area around Wadi Ham well field is about 5.0×10^6 m^3/a, which is slightly less than the total recharge into the system from both the recharge site and over the rest of the aquifer.

(g) the model is believed to have been prepared with an adequate accuracy for processing additional development scenarios, such as shifting current pumping locations along the coast to further inland, and quantifying the benefits. Yet there is not much room for maneuvering. There is very little outflow from the aquifer side into the sea, on the contrary, sea water intrusion balances the head decline created by groundwater abstraction.

Records of hydrochemical data indicate that the salinity increase of groundwater exploited by the well field, may, in general, remain at moderate salinity levels.

APPROACHES TO GROUNDWATER MANAGEMENT SCHEMES

The following main conclusions can be derived from the results of investigations in the Fujayarah coastal plain:

- The Wadi Ham dam as an artificial recharge device and the Shaara well field in the wadi section downstream of the dam provide an efficient set - up for management of the available fresh water resources.
- Groundwater extraction further downstream in the wide coastal plain is highly endangered by sea water intrusion.

- The only practical option for improvement of the quality of brackish water in the area near the coast is a drastic reduction of groundwater withdrawal.

The modeling results indicate that there are possibilities to push back the sea water intrusion and to improve the water quality at least in parts of the coastal plain. As preconditions, a balance has to be maintained between groundwater replenishment and groundwater extraction, and production wells have to be concentrated at sites, which are not directly endangered by sea water intrusion. According to an approximate water balance of the Fuajyarah - Kalba coastal area in years with average rainfall, renewable fresh water resources of around $5x10^6$ m^3/a are confronted with groundwater extraction of about $5x10^6$ m^3/a. Additionally, water for domestic use is supplied from desalination plants. The deficit created by the over-extraction is compensated by declines of water levels and inflow of sea water. Sea water intrusion in the area covered by the Wadi Ham model is around $3x10^6$ m^3/a.

The following possibilities may be considered for improvement of water quality and sustainable fresh water exploitation in the area between Wadi Ham and Fujayarah City, corresponding approximately to the model area;

- Reduction of the groundwater extraction in areas near the coast through a wider introduction of modern water saving irrigation techniques and conveyance of water from an expanded well field in the Shaara area to the irrigation areas;
- Further substitution of groundwater extraction for domestic supply through an additional desalination plant;
- Infiltration of treated waste water into ponds near the coast.

For the planning of such management measures, further detailed monitoring of groundwater extraction and of groundwater levels is needed as a basis for additional model runs.

The prospects for successful groundwater management in the coastal area around Fujayarah appear promising, but possibilities of expansion of management strategies to the Kalba area further south may be limited by the shortage of available fresh water resources, necessitating eventually a substantial reduction of agricultural areas recharge is under construction.

The strategy for groundwater management can, in principle, be transferred to other parts of the coastal area, e.g. the Wurrayah coastal plain north of Fujayrah, where a wadi dam for artificial recharge is under construction.

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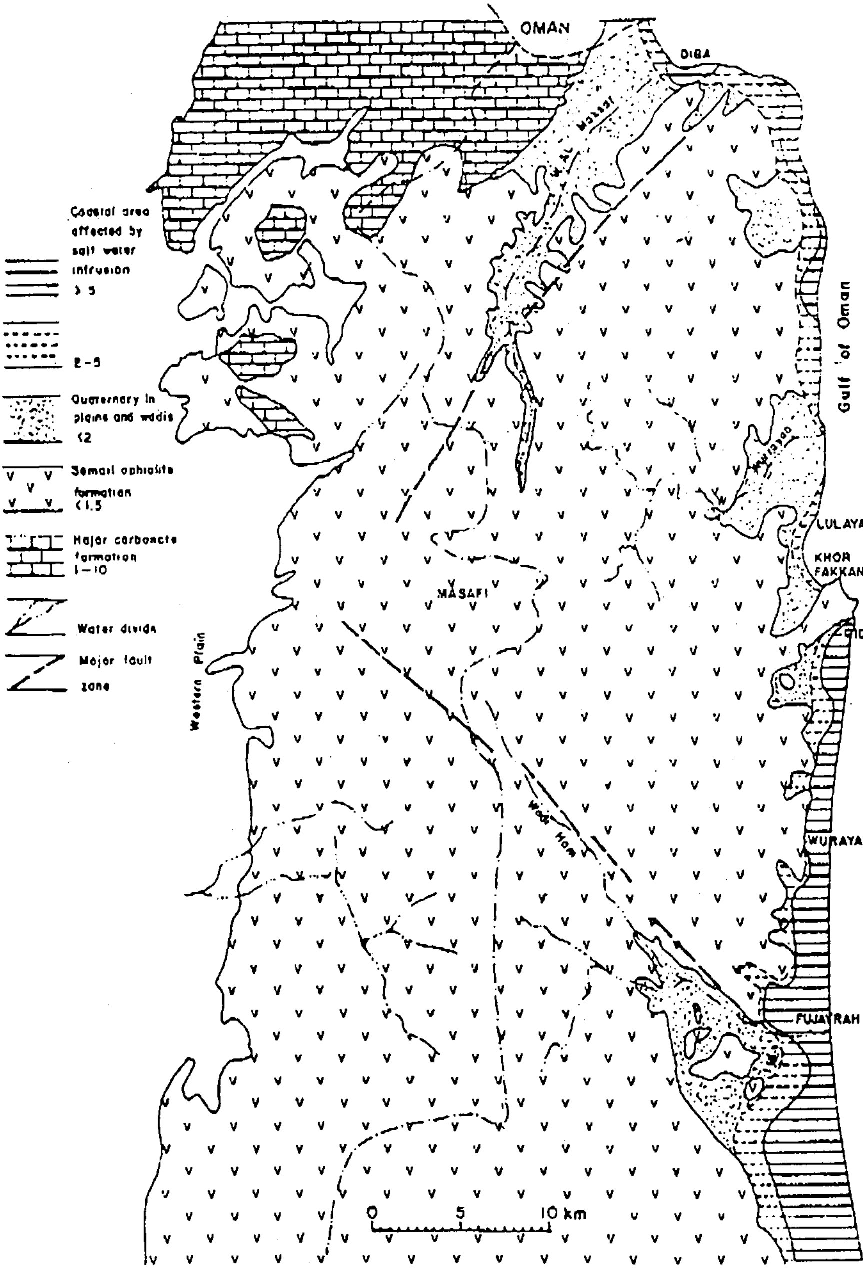

Figure 1: Sketch map of the eastern coastal plain and adjoining Oman Mountains

GENERAL LOCATION MAP OF WADI HAM MODEL

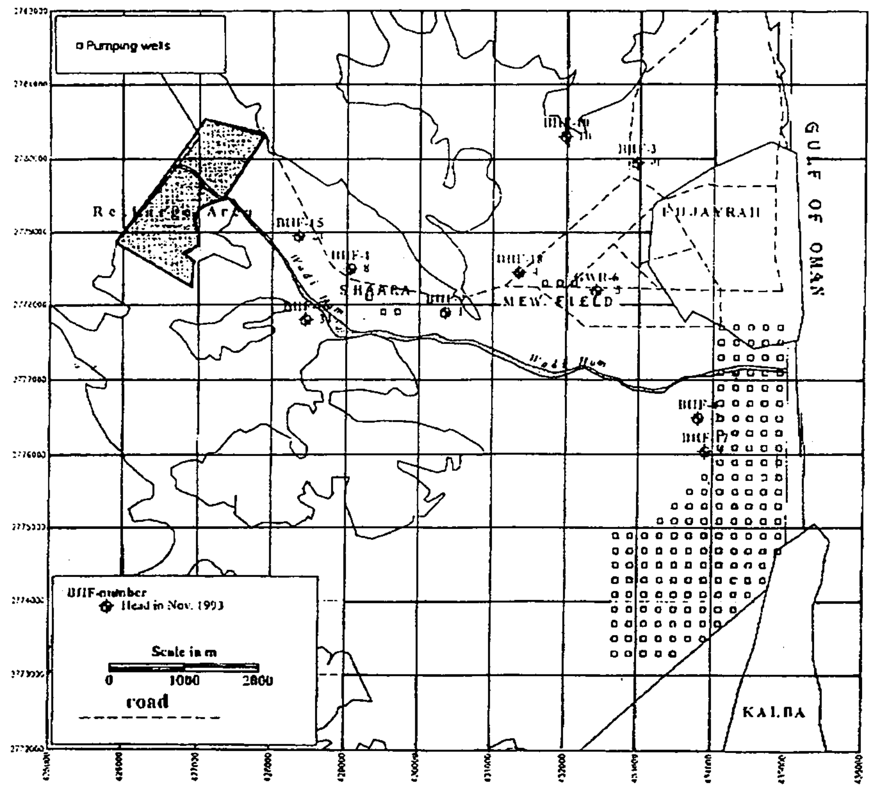

Figure 2. Wadi Ham General Location Map

Screening of Recharge Dam Sites in Oman

Suleiman Al Akhzami, William O'Brien and Ian Cookson

SCREENING OF RECHARGE DAM SITES IN OMAN

Suleiman AI Akhzarni, William O'Brien and Ian Cookson
Directorate General of Water Resource Assessment
Ministry of Water Resources, Sultanate of Oman

ABSTRACT

The hyperarid country of Oman has utilized recharge dams to catch irregular, and precious, flash floods and give them opportunity to infiltrate into groundwater storage. As of 1996, the Sultanate has built 20 major dams that augment natural recharge and reduce the waste of flood water to the sea or the desert. The first screening of recharge dam sites in Oman was reported by Hydroconsult (1985), but was based on less than 5 years of flow data from what is now generally considered a wet period, had little information on aquifer properties, and no incountry experience with recharge dams. In 1995, with more hydrologic and groundwater data, and experience gained from 10-years of construction and maintenance of dams, the Ministry of Water Resources (MWR) undertook a new screening program for remaining dam sites.

The two-stage screening process was limited to large catchments (greater than 100 km^2) that did not already have a dam or a completed feasibility study. Field visits and data analysis were made at sites that passed certain "stage one" criteria. Of the 78 potential dam sites examined, 13 passed through the screening steps and were nominated for feasibility level studies. Many sites did not appear feasible for recharge dams, but alternative development options were recommended such as boreholes, falaj support wells, or underground dams. This paper outlines the criteria and principles used in the screening process, and gives a detailed description of screening considerations for two dam sites that typify Oman's interior and coastal regions.

Keywords: Groundwater Recharge, Dams, Dam Site Selection, Oman

INTRODUCTION

The Sultanate of Oman occupies a strategic position at the southeast corner of the Arabian Peninsula. The climate is considered hyperarid, with highly variable rainfall that averages about 100 mm/year. Groundwater is the main water source, harvested by wells or falaj (ganat) collector tunnels. The wadis, usually dry river beds, suddenly fill with flash floods when rainfall occurs. Some of the floods infiltrate naturally, but in many years there are losses to the sea or desert of millions of cubic meters of water.

Recharge dams represent one of the few practical tools available for surface water management under Oman's conditions. Although their impact on the Sultanate's total fresh water availability is modest, they enable recharge to be directed to key locations of water deficit or of development potential, and they make beneficial use of sizable flood flows otherwise lost to the sea or desert. From 1985 to 1996, Oman has built 20 major dams, of which there are 16 recharge dams and 4 flood-control dams that augment groundwater recharge (see Figure 1).

The previous effort to screen and prioritize recharge dam sites in Oman was by Hydroconsult (1985). This study was based on a very short data record (generally less than 5 years of flow data) that is now considered to be a wetter period than average. At that time there was no incountry experience with building, operating and maintaining recharge dams. Also, there were few boreholes with recorded lithology, and aquifers were not well defined.

Since then, recharge dams have gained in popularity, and there are hundreds of potential recharge dam sites that have been proposed throughout the Sultanate by planning studies or by citizens' requests. Also the water resource data base is now 10-years longer and aquifers in recharge areas are better defined by borehole projects and geophysics traverses. Because of these factors, and the high cost and commitment required for feasibility studies, the Ministry of Water Resources (MWR) initiated a new screening study in 1995 to help select the most promising dam sites for detailed feasibility study.

The aim of the new screening programme was to present:

* A list of sites recommended as technically suitable for feasibility study.
* An appraisal of the best sites, with data and descriptions collected to prepare terms of reference for feasibility study.
* Recommendations for required improvements to the hydrometric monitoring network for hopeful schemes.
* Suggested packaging of feasibility studies on adjacent or nearby catchments.

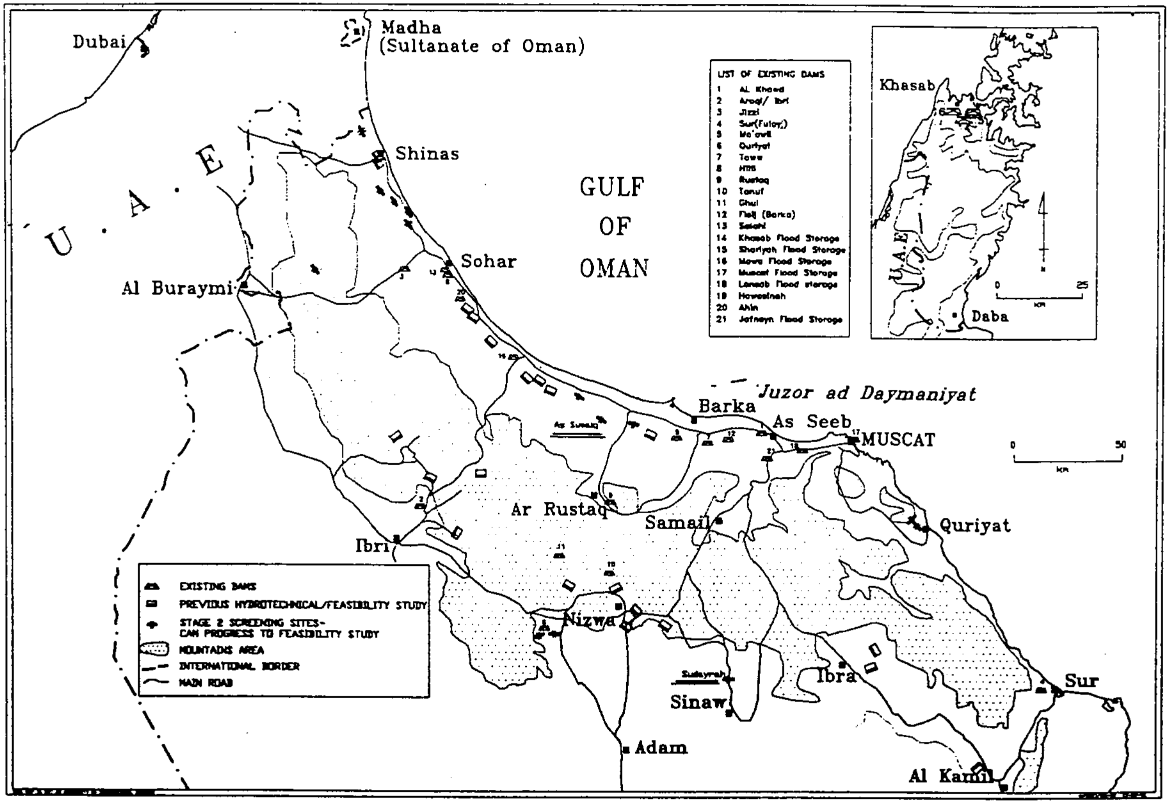

FIGURE 1. LOCATION OF EXISTING AND PROPOSED DAMS IN NORTHERN OMAN

The screening process consisted of two stages. The first stage was to list all the proposed sites and make comparison with the screening criteria at a desk study level. The sites that were still favorable were then promoted to stage two, where a site visit and further analysis were made. Recharge schemes with catchment areas greater than 100 km^2 were selected for the first round of screening because they offered, on a national scale, the best potential for major impact.

For each site, it was sought to establish that there was:

* a clear need for the water
* adequate surface flows
* sufficient and accessible alluvial groundwater storage
* a suitable site for construction
* no significant loss of water supply for downstream users

This paper describes the criteria and principles used in the "large catchment" screening process, and gives a detailed description of how the screening process was applied to two sites that typify Oman's interior and coastal regions.

THE SCREENING PROCESS

As sand and gravel are screened to sort various sizes of construction material, dam sites were screened to find the most beneficial, and worthy of implementation. Selected indicators of feasibility were used as the "*screen*" which the recharge darn sites were evaluated. The screening was done in two stages to reduce the amount of work on schemes that had little potential. The two stages of screening and level of analysis were:

Stage 1 List previously suggested sites and make initial evaluation based on general criteria at desk study level.

Stage 2 Make site visits to those sites that passed Stage 1, analyze available data, and make an assessment of likely feasibility.

For the Stage 1 screening, 78 previously suggested "large catchment" recharge dam sites were identified and listed. These essentially constitute all the major schemes that have been previously proposed in the Sultanate. Where a number of options were proposed for a particular wadi, the scheme was only listed once.

Obviously, not all of the criteria had supporting data for all the sites. However, enough details were readily available or easily deduced that provided a reliable indication of the feasibility of each site.

Twenty-six (26) large catchment sites of the Stage I list were recommended to be forwarded for Stage 2 screening. These schemes comprised of, for the most part, the last downstream user for a given catchment, and usually represented the last place where water loss to the sea or desert could be prevented. Such sites have the advantages of not adversely affecting downstream users, and allowing the maximum amount of natural infiltration to occur upstream, thus keeping dam sizes to a minimum.

The list of 26 schemes for Stage 2 screening was not considered definitive, and after further steps to prioritize schemes the list may be revisited. For example, reallocation of water resources to upstream users in a catchment by a dam may become acceptable if adequate and economic alternative water supplies can be provided to those downstream. However, it is thought that such instances would be exceptions, and such assessment would have to be on a individual site's merits, rather than as part of a national screening process.

Finally, thirteen (13) sites were recommended for feasibility studies (shown on Figure 1), 8 of these being along AI Batting coast where the large catchments and deep alluvial aquifers favor recharge dams. Where a recharge dam scheme was identified as unhopeful, groundwater management planning for that area should be directed toward other development options.

SCREENING CRITERIA

Some criteria result in exclusion of the scheme, while others promote it toward feasibility. At Stage 1, it was not possible to cover all aspects fully, but whatever could be readily discovered was used to refine the list for Stage 2. The result was a list of obviously hopeful schemes, plus all those schemes which could not be eliminated by a critical feature.

Factors that promote a site to further study

* **Clear benefits to target user:** Are there clear needs for additional recharge to reduce a deficit or for potential development, would flood control benefits be significant? Situations calling for urgent action are in localities that include declining falaj flows, declining groundwater levels, have many applications for well permits, and have deteriorating water quality or saline intrusion. It was considered that schemes aimed at addressing existing needs of declining groundwater availability and deteriorating water quality should take priority over proposals relating to new developments. Since sauce-economic evaluations are outside the scope of this screening, both are included in Stage 2.

* **Significant surface water potential:** Estimate of flood flows to the dam sites and what is wasted to the sea or desert indicate the likely magnitude of benefits of a dam project.

* **Suitable recharge area and hydrogeological conditions:** At Stage 1, it was not possible to assess in detail the hydrogeological suitability of schemes such as infiltration characteristics, available alluvial storage, and recoverability of the groundwater by the target users. However, whatever can be readily recognized was used to refine the list for Stage 2. In Stage 2, the site visit and further analysis were indicative, but still not definitive, and this subject will require specific drilling and geophysics at the feasibility level.

* **Suitable conditions for construction of dam:** Is the dam site satisfactory for reservoir storage, proximity to target area, foundation conditions, proximity of construction materials, and unlikely to interfere with major roads, property, etc.?

* **Acceptable impact on existing aflaj:** Although there is no general MWR policy with regard to construction of recharge dams over aflaj, such activities are considered undesirable, particularly in terms of the significant responsibilities assumed for falaj flow. Where a falaj was known to exist beneath a proposed site, a field check was made to see if alternative sites were available.

* **Acceptable impact on the environment:** Would there be significant displacement of natural habitat, population, agriculture, and communication / utilities? Would there be spread of existing water quality problems?

Factors that exclude site from further screening

* **Previous feasibility study**

* **Major users downstream of the scheme target:** Construction of a large dam in the upper catchment would essentially constitute a reallocation of water resources to upstream users. Where downstream users are already experiencing water shortages, the upstream sites were not forwarded to Stage 2.

* **Existing dam on the wadi:** A scheme is not forwarded to Stage 2 if it was proposed on a catchment where an existing dam clearly limits the scope for an additional major structure. It was assumed that sediment considerations and flood-proofing a series of small darns would prove more expensive

than single large dams proposed in this screening. Improving the water management of catchments that have existing dams is to be the subject of other studies.

* **Other water development options were obviously preferable:** If it was possible to determine that a less costly solution to water development would meet the water needs, then the site was excluded from further screening. These methods of water management include well fields, underground dams, trucking water, extension of falaj or falaj support wells.

TWO CASE STUDIES

Two sites are selected for detailed description to demonstrate how the screening process works under Oman's conditions.

One site, Suwayq, is in Al Batinah Region, along the coast of the Gulf of Oman. The wadi system emerges from the Jabal Akhdar mountain range and passes across a 20 km wide plain to the sea via braided alluvial channels. For this site, the main water resource considerations are extensive agriculture development supported by well water, a water balance deficit which causes saline intrusion, deep alluvial aquifers created by alluvial fan development, and flood water wasted to the sea.

The other example, Sudayrah, is an interior site with recent agriculture development, water supply by wells and falaj systems, and where excess flows are wasted to the desert. This wadi flows from the Al Haar Ash Sharqi mountain range along alluvial channels that flow toward the extensive and famous Randat al Wahaybah (Wahaybah Sands), then on to the sea.

Suwayq - Al Batinah (Coastal) Region

This scheme is located on Al Batinah coast to support the rapidly developing Suwayq area, about 100 km west of Muscat. The agricultural area has been expanding until the last few years. Residential and commercial areas are continually developing along the highway. One concern is that nearby gravel quarries are being used for landfill and groundwater pollution may occur. Catchment features, hydrometric monitoring network, and the proposed dam site are shown in **Figure 2.**

The aim of the dam is to recharge flood water that is wasted to the sea in order to reduce a groundwater deficit and the rate of sea water intrusion. Flood control benefits would also be expected.

Wadi Bani Ghafir serves this catchment, and originates at the 2,600 m elevation of the Jabal Akhdar mountains. The upper catchment geology is composed of Hajar Super Group carbonates, then the mid-catchment narrows through Samail nappe ophiolites. There is significant alluvial cover throughout and alluvial fan development downstream of the jabal front. The broad, gently sloping coastal plain is characterized by shallow, highly-braided channels, with more deeply incised channels and ancient terraces near the jabals.

Site description

The original site as proposed by Hydroconsult (1985), had envisioned diversions to channel some of the braided channels to the dam site, even channels that are 5 km from the main dam site (see Figure 2). These diversions may not be appropriate now because of development since that report, but with a dam site at this location or just upstream, it is possible to capture most of the flows wasted to the sea. Construction materials are available and foundation conditions are expected to be manageable.

Hydrology

The catchment area to the dam site is 655 kM^2 and it is about 70 km from the top of the catchment to the coastline. The average of MWR's (1996) annual rainfall isohyets to the dam site is 139 nun. Most of this rainfall is lost to evaporation and recharge, leaving runoff estimates to the dam of 1.5 Mm^3/yr (1.7% of rainfall), and 0.7 Mm^3/yr (0.7% of rainfall) wasted to the sea. The runoff estimates are based on MWR (February, 1996) runoff curves for the region. Wadi gauge data in the catchment supports these estimates.

The catchment has an adequate number of surface water gauges. There are 4 wadiflow gauges with records beginning in 1983. The wadi gauge nearest the coast has channels that sometimes bypass it, and it should be re-evaluated. Of the 7 historical rain gauges, 6 are now active. One rain gauge has records beginning in 1974, but the remainder begin in 1983.

Hydrogeology

A total of 11 monitoring boreholes are in two portions of the study area, in the mid-catchment alluvium and along the coast. The n-dd-catchment wells show a distinct rapid and peaky response to recharge. Further down the fan, the wells show a similar but more attenuated response, and a significant time lag, for example, the 10 m rise in groundwater levels after the wet 1982-83 flood events took place over a 2-3 year period.

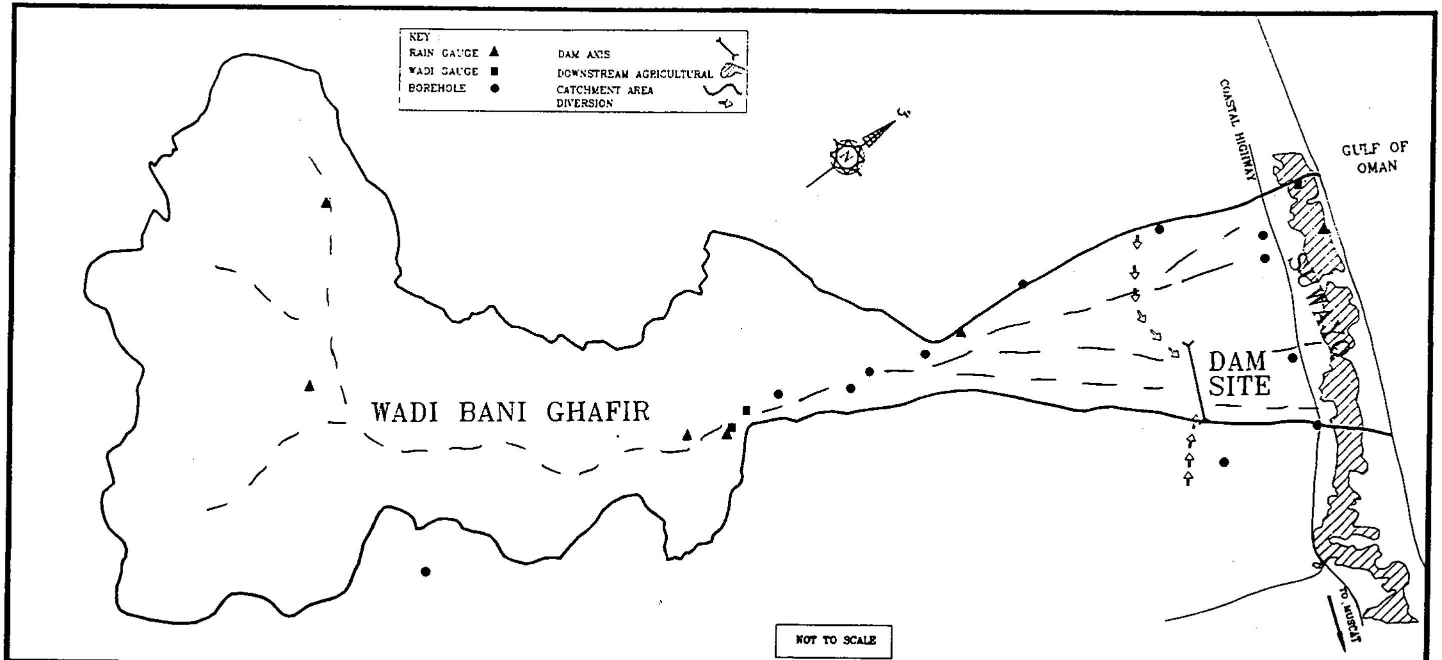

FIGURE 2: SUWAYQ RECHARGE DAM SITE

The Suwayq area is experiencing deteriorating groundwater quality, with inland encroachment of sea water. There is a clear trend of declining water levels in monitoring wells up to 14 km from the coastline. In 1995, the water levels 4 km from the sea coast were 0.6 m below sea level. Superimposed on the steady water level decline is a cyclical response to abstractions with lowest water levels occurring over the summer months. The decline in groundwater levels indicates a serious water balance deficit, that the abstractions are exceeding the natural supply. The increasing salinity of water near the coast confirms this trend.

The infiltration and aquifer characteristics appear to be suitable for a recharge dam. Studies of infiltration rates in similar and nearby catchments show good potential for recharging the alluvial fan into the main aquifers that benefit the target user.

Recommendations for Suwyaq site

This site is recommended for feasibility level study, with some urgency because of the increasing sea water intrusion. Other water management options also should be considered, such as restricting abstraction and protecting groundwater from pollution. The neighboring catchment is currently subject to detailed MVVR assessment, whose results will help provide a sufficient data base for feasibility investigations. An additional wadiflow gauge is recommended to better measure the higher flows.

Sudayrah - Ash'Sharqiyah (Interior) Region

The Sudayrah recharge dam is proposed in the Ash'Sharqiyah region, in Wadi Samad, about 135 km south-southwest of Muscat, just upwadi from the agricultural centers of Sudayrah and Sanaw. These are the last main towns before Wadi Samad runs into the Wahaybah sands.

Recent expansion of date groves at Sanaw have created declines in the water table, increasing brackishness of the water, and acting as a stimulus for applications for MWR permits for new wells and deepening existing wells. New roads and other infrastructure have encouraged residential and commercial development. Catchment features, hydrometric monitoring points, and the dam site are shown on Figure 3.

The main purpose of this dam would be to capture flows currently lost to the desert south of Sanaw, and to reduce groundwater deficits. The main beneficiaries would be Sudayrah, Mntrib, and Sanaw. Some degree of flood control would benefit Sanaw.

Wadi Samad is one of the main sub-catchments of Wadi Andam which drains the Al Hajar Ash Sharqi mountains. It is a long narrow basin, reaching 1,300 m in elevation at the top and about 400 m elevation at the dam site. The catchment geology upwadi of the dam site is allochthonous material of the Samail nappe ophiolite, with alluvial terrace deposits along the wadi course. From the dam site to Sanaw, the catchment is characterized by extensive alluvial terraces and local outcrops of Hawasina limestone. After Sanaw, the wadi runs into the extensive Wahaybah sands.

Site Description

A dam could be constructed in the reach near the village of Khashbah and upwadi of the mother well for the Sudayrah falaj (Wakuti, 1990). Other sites, but less likely feasible, were also suggested further downstream by Hydroconsult (1985) and MWR (April, 1995). Cemented alluvial terraces, less than 2 km apart, would form abutments at the Khashbah site, and the recharge area would extend for 14 km to Sanaw. Construction material is available and foundation conditions appear favorable.

The falaj mother well for Sudayrah is 300 m downstream of the dam site, which means releases from the dam would impact the falaj directly, and would likely extend the length of time the falaj would run at high levels. Protection of the falaj and the reaction by the local falaj community were major factors in screening this site, and could potentially limit the feasibility.

Hydrology

The catchment area to the dam site is 534 km^2, and the dam is about 35 km from the highest point of the catchment. The average of the MWR (1996) annual rainfall isohyets to the dam site is 147 mm. Most of this rainfall is lost to evaporation and recharge, leaving runoff estimates to the dam of 2.5 Mm^3/yr (3.2% of rainfall), and wasted to desert 3.1 Mm^3/yr (3.1%). The runoff estimates are based on 8 years of record at the Sanaw and Samad wadi gauges.

This wadi has two rainfall gauges and two wadiflow gauges. Flow records begin in 1983-4, and the rainfall in 1993. In the neighboring catchment there is a rainfall gauge that started recording in 1978. The upstream wadi gauge at Samad records numerous small events, but these infiltrate by the time the wadi reaches the downstream gauge at Sanaw. The flow record at Sanaw only shows two large flow events, indicating the recharge dam would be targeting rare but large events. Providing a safe spillway design may become a costly aspect of this proposed dam.

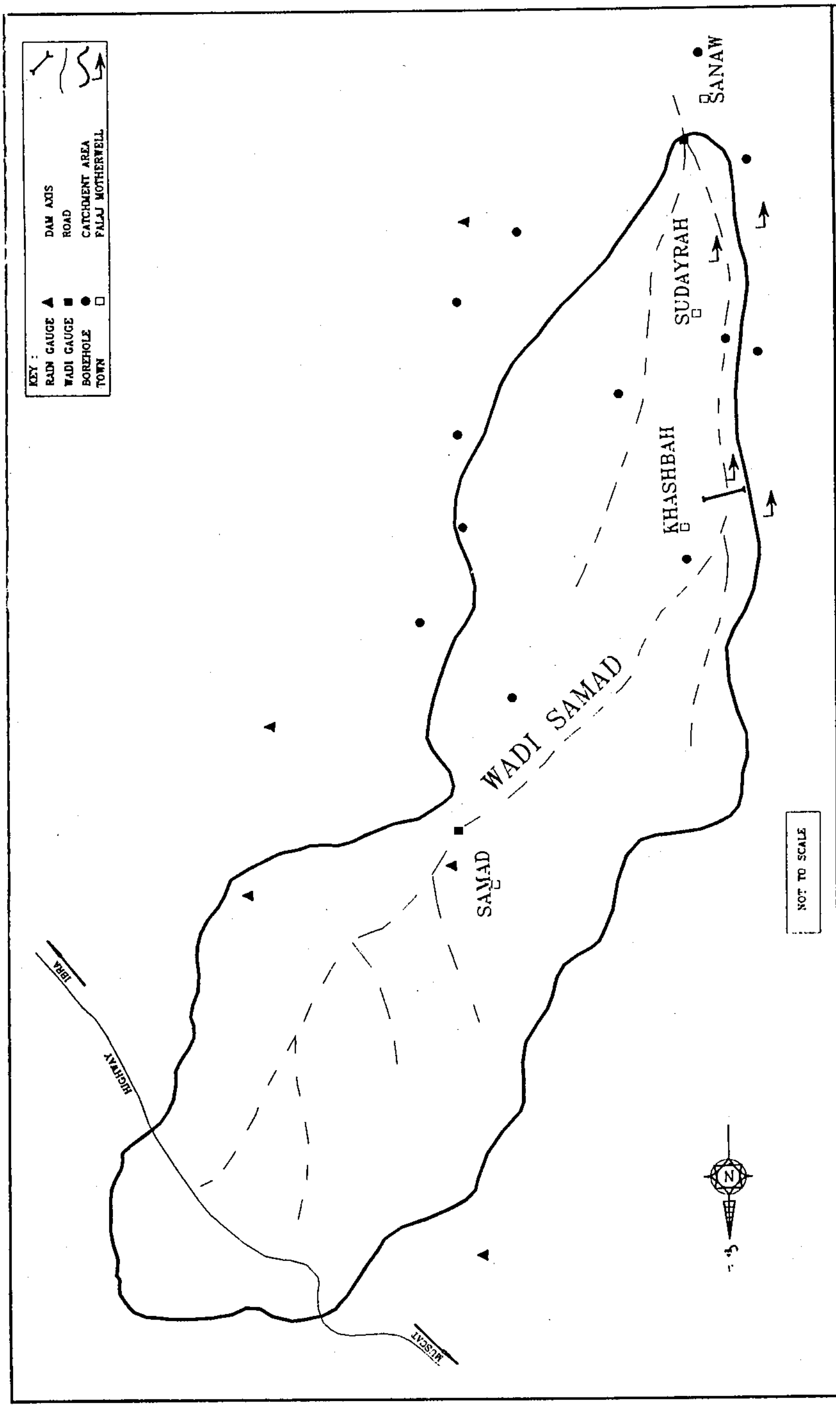

FIGURE 3: SUDAYRAH RECHARGE DAM SITE

Hydrogeology

There are 6 monitoring boreholes in the catchment, and others nearby. Most of these were drilled in 1994, so have a very short record. Two boreholes have records beginning in 1984. The closest to the dam site is about 4 km away. Three falaj are monitored in the area, including Falaj Sudayrah.

The cemented alluvial channels lin-dt available alluvial storage, which may in turn limit the size of the dam. The other proposed sites further downstream would be even more severely limited by this factor. However, there is evidence of higher permeability layers. The aflaj show relatively stable flow even during the dry years of 1992-94, indicating that they are tapping higher permeability strata along the wadi. A new municipal well close to the wadi at Sudayrah is also reported to be high yielding.

Groundwater levels in the older wells have historically been fairly stable, but these are some distance from the wadi. The new wells in the wadi channel have water levels about 9 m bgl. One well in the wadi with a longer record shows that after the extreme flow of 1987, water levels came to within 3 m bgl, but data are questionable.

Recommendations for Sudayrah dam site

This site is not recommended to proceed to feasibility studies at this time. Technical and social issues related to building so close to the falaj mother well need to be resolved prior to detailed feasibility study. Increased frequency of monitoring groundwater levels and falaj flow is recommended to better define the groundwater reaction to flood events, for estimating available alluvial storage, and to create a longer data record to observe trends. Baseline monitoring of water supplies for the few small villages downstream of Sanaw is also suggested.

CONCLUSIONS AND RECOMMENDATIONS

The aim of the screening was accomplished, to produce basic technical evaluations of the many proposed dam sites, and to develop a short list of sites that are recommended to proceed to feasibility study. The screening was based on technical issues, and social, economic, and political issues will next be addressed in the Sultanate's planning process. The concept of screening before expenditure is necessary in a budget-conscious atmosphere, and can be applied to any number and types of projects.

Certain issues of water allocation were raised, and the trend was to recommend the downstream sites, in order to minimize negative effects on downstream users.

Of the 13 dam sites recommended, 8 are along Al Batinah coast, where conditions of large catchment, water balance deficit, deep alluvial aquifers, and flow wasted to the sea strongly support recharge dams. The case study for the Suwayq site exemplifies this.

The screening criteria were stressed more by the interior sites. The conclusions were not always so clear as for other parts of the Sultanate. Suitable interior sites were more difficult to find since they had more limited alluvial storage and were often too close to existing aflaj. The Sudayrah site exemplifies this. Increased monitoring at this site is recommended, and then a review of the screening conclusions.

Many of the catchments had short periods of record or few monitoring stations. Recommendations were made for development of the wadiflow, rainfall and groundwater monitoring stations. Records are still relatively short for planning and design of dams. Commitment to a long term data collection and analysis effort is strongly recommended.

ACKNOWLEDGMENTS

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Application of One Dimensional Flow Modelling to Estimate Groundwater Recharge—Al Batinah, Sultanate of Oman

Richard Lakey and Habiba Al Hina

APPLICATION OF ONE DIMENSIONAL FLOW MODELLING TO ESTIMATE GROUNDWATER RECHARGE—AL BATINAH, SULTANATE OF OMAN

Richard Lakey and Habiba Al Hinai
Water Resources Modelling Section
Ministry of Water Resources
Sultanate of Oman

ABSTRACT

One dimensional flow modelling of the unsaturated zone has been undertaken for major soil types on the Batinah coastal plain in northern Oman (Figure 1), to gain more insight into recharge processes in irrigated and non irrigated areas. Observation well hydrographs in the coastal zone indicate a good correlation between recorded water table rise and rainfall which is very difficult to explain by any process other than recharge. This response is only observed in irrigated areas along the coastal strip. Batinah soils are of moderate to high permeability, non swelling, and generally well drained. The water table occurs at 10 to 15 meters below ground surface in the coastal zone and at greater depths further inland. Unsaturated zone modelling based on Richards' equation, indicates that under irrigated conditions a high soil moisture level is maintained and piston flow occurs in response to rainfall, or anomalous irrigation, resulting in a rapid water table response which is much shorter than the transit time. In this situation very high recharge is possible under ideal conditions. However, in non irrigated areas where soil profiles gradually drain to very low moisture contents, rainfall infiltration is either removed by vegetation or soil evaporation, or marginally increases the soil moisture content with no significant increase in drainage to the water table.

Keywords: Oman, infiltration, modelling, arid zone, soil type.

INTRODUCTION

An understanding of infiltration and subsequent movement of water in soil is becoming increasingly important in soil science, hydrology, agriculture and resource management. The focus in this study is on hydrology and more specifically on groundwater resources. Surface water ponding, runoff generation and related processes are not considered in this approach where the emphasis is on gaining a first approximation of profile drainage (recharge), for a number of situations encountered on the Batinah plain. The objective of this work is to obtain a better estimate of recharge for regional groundwater flow modelling on Al Batinah.

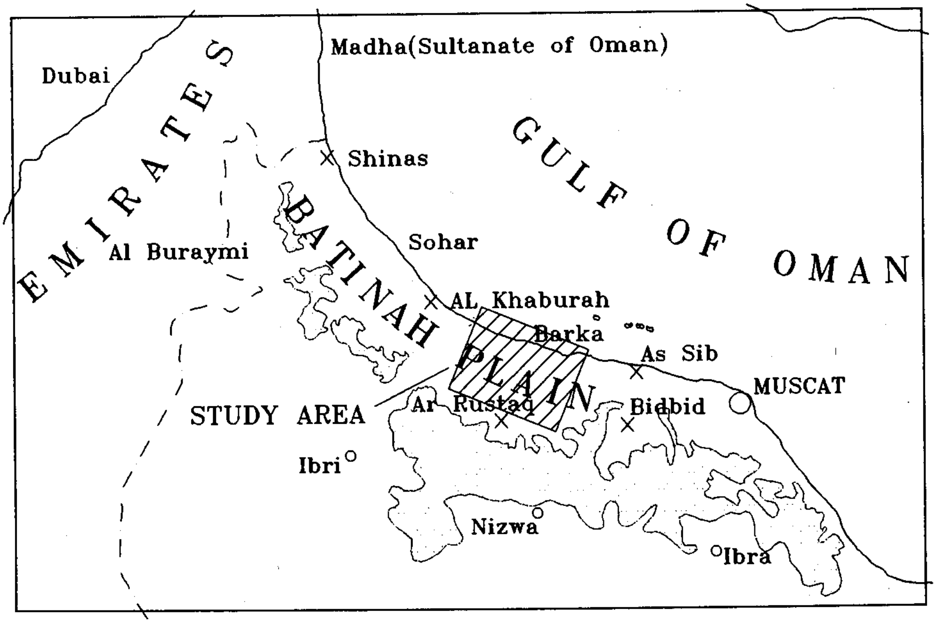

Figure 1 Study area location

CSIRO, Australia have developed a model for soil water infiltration and movement. This model (SWIM) has been applied in this study. The SWIM code provides a computationally efficient means of solving the Richards' equation, which is the commonly accepted basis for detailed studies of soil water movement. The underlying principles are briefly explained below (Ross, 1990).

Darcy's law for one dimensional flow of liquid water in soil is:

$$q = -K \frac{dH}{dx}$$

where:

q is flux density (cm/h)
K is hydraulic conductivity (cm/h)
H is hydraulic head at position x in the direction of flow.

This law states that water flows down the hydraulic gradient at a rate proportional to the gradient. K varies with soil type and moisture content but not with gradient.

The equation of continuity for a fluid of constant density is:

$$\frac{\partial \theta}{\partial t} = \frac{\partial q}{\partial x} + s$$

which simply states that the rate of increase = flux in - flux out + rate of addition.

where:

θ is volumetric water content
t is time
s is source strength, i.e. cm water per cm distance per hour.

Combining this last equation with Darcy's law gives Richards' equation for one dimensional flow of liquid water in soil:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} K \left(\frac{\partial H}{\partial x} \right) + s$$

If it is then assumed that gas pressure in the soil is always atmospheric, i.e. that air can move freely, and that we are dealing with a rigid soil structure, H is given by the sum of the matric potential Ψ (cm) and the gravitational potential z, which is equal to the elevation in cm from some arbitrary reference level. Richards' equation then becomes:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} K \left(\frac{\partial \Psi}{\partial x} + \frac{\partial z}{\partial x} \right) + s$$

This is the equation solved by the SWIM model.

The SWIM code has the following features:

- efficient numerical solution of Richards' equation;
- conservation of mass, even in fast approximate solutions;
- ability to handle non uniform and layered soils;
- ability to handle unsaturated, saturated and ponded conditions;
- transient soil conductance and storage;
- calculates evapotranspiration, runoff and drainage.

Assumptions and limitations include:

- not applicable to swelling soils; simplified forms for hydraulic properties may not always be applicable;
- where sparse macropores are present, Darcy's law is not strictly applicable; the assumption that water at the same depth is in equilibrium, may be invalidated;
- calculation of actual evapotranspiration introduces many simplifications;
- vapour flux in soil is ignored; temperature effect on water fluxes are ignored;
- hysteresis in the soil moisture characteristic and hydraulic conductivity functions is ignored.

The data required to address many of these limitations are generally only available for a few site specific research stations, where comprehensive measurements have been made. To the authors knowledge no such sites exist on the Batinah. Batinah soils are non swelling with good internal drainage and as such are suitable for simulation by SWIM, using simplified forms for hydraulic properties. Macropores do exist and are generally associated with root cavities, but these seldom extend throughout the profile except where the soil profile is quite thin (less than a metre).

DISTRIBUTION OF SOILS ON THE BATINAH

Soil studies undertaken by the Ministry of Agriculture and Fisheries (MAF), have revealed that all Batinah soils are either Entisols or Aridisols. Entisols are soils that show little or no evidence of development and have no diagnostic horizon, other than an ochric epidon (light coloured surface horizon with low organic matter). Entisols are found in young alluvial deposits and aeolian sands and are represented by fluvients, orthents and psamments on the Batinah.

Fluvients are the dominant soils on the Batinah and are mostly of sandy or loamy texture (some silty), and always include at least one loamy or finer layer. Orthents form in gravely and sandy, gravely deposits. Torrifluvients (60%) and torriorthents (20%) together comprise about 80 % of the arable soils on the coastal plain. The prefix *"torri"* indicates that these soils have a torric, or very hot and dry moisture regime.

Aridisols have at least one diagnostic subsurface horizon and an aridic moisture regime. They cannot provide water to mesophytic plants for long periods of time. Salorthids, however may have an aquic moisture regime. Gypsiorthids, Calciorthids and Salorthids, are the only Aridisols found on the Batinah coastal plain. These soils are generally unsuitable for cultivation.

Gypsiorthids are the most extensive Aridisol in Oman and on the Batinah. They have a gypsic horizon and are mostly encountered on old landforms, such as alluvial fans and terraces. They often feature a compact layer, cemented by gypsum and referred to as a gypsum pan (Petrogypsic horizon). Calciorthids have a calcic horizon, form on residuum and alluvium, are generally strongly calcareous, non saline to strongly saline, gravely and deep to moderately deep. Salorthids are very saline soils formed in wet depressions, where capillary rise and evaporation concentrate highly soluble salts in a diagnostic salic horizon.

RELATIONSHIP BETWEEN SOIL TYPE AND HYDROGRAPH RESPONSE

Examination of continuous chart recorder data for groundwater observation bores monitoring the water table on the Batinah coastal plain revealed a good correlation between recorded water table rise and rainfall for some bores, which is very difficult to explain by any process other than recharge. Further analysis showed that all bores which appear to respond to rainfall are located in areas covered by Entisols which have been developed for irrigated agriculture. On the other hand, those bores which do not show a direct response to rainfall are related to soils which are not suitable for cultivation and are not irrigated. Most of these bores are located further inland, in areas covered by very coarse, gravely torriorthents or gypsiorthids and show a pronounced lagged hydrograph response.

It was postulated in an earlier paper (Lakey et al, 1995), that depth to water table might exercise significant control over hydrograph response on the Batinah plain, i.e., that gradual, downward movement of a recharge pulse through a thick unsaturated zone could generate the smoothed and lagged hydrograph response observed for deeper water tables further inland.

More recent analysis has shown that while all bores which feature a rapid hydrograph response to rainfall have water tables less than 25 mbgl and bores which feature a lagged response generally have deeper water tables, some wells with a pronounced lagged response, have quite shallow water tables. However it was found that these bores are not constructed in Recent or Sub Recent alluvium, but instead monitor limestone or Ancient alluvium. The pronounced lagged hydrograph response is now considered to be primarily a feature of older, more consolidated formations and is not evident in wells monitoring younger alluvium.

This indicates that depth to water table may not be the primary control and other factors must be involved. The observed relationship between hydrograph response and irrigated agriculture suggests that the soil moisture regime, may be the dominant factor. SWIM models were set up and run for the three major soil types (torrifluvients, torriorthents and gypsiorthids) to examine soil water movement under irrigated, and non irrigated situations. The effect of vegetation has also been considered.

The soil moisture characteristic and the unsaturated hydraulic conductivity function are the only two soil element properties required to solve the Richards' equation. MAF, undertook some 356 infiltration and permeability tests, carried out extensive water content determinations at 0.3 and 15 bar and provided comprehensive textural descriptions, size analyses and soil chemistry data.

Torrifluvients feature moderate vertical hydraulic conductivity and moderate to high water retention difference (AWC). Torriorthents have high vertical hydraulic conductivity but because of their very gravely character a low water retention difference. Gypsiorthids display moderate to high vertical hydraulic conductivity and moderate to high water retention difference. The water retention difference is defined as the amount of water a soil can hold between 0.3 and 15 bar within the root zone (taken as 1.5 m below the surface, or the distance down to a limiting layer). It provides an indication of the amount of water available for plant use. Value ranges for each soil category are given in Table 1 below.

Table 1 Classification ranges for soil hydraulic properties

Soil category	AWC (cm/150 cm)	Vertical hydraulic conductivity (cm/h)
Very low	<6.5	<1
Low	6.5 - 13	1 - 3
Moderate	13 - 19	5 - 15
High	19 - 25	15 - 25
Very high	>25	>25

Source: United States National Soils Handbook (USDA - SCS, 1983)

ONE DIMENSIONAL FLOW MODELLING

Parameters and assumptions employed in the SWIM modelling include:

- daily time step;
- average water table depth of 20 m;
- soil properties and vegetation characteristics as set out in Tables 2 and 3; these parameters are fully defined in the SWIM model manual, and are further described in Campbell, G. S. (1985);
- preferential pathways do not penetrate the full profile and are not significant;
- 10 soil layers (to provide definition), but each layer has the same soil hydraulic properties, i.e. a uniform soil profile;
- daily rainfall for the period October 1976 to October 1990 can be approximated by rainfall recorded at a centrally located rain gauge on the Batinah, (average MAP approximately 100 mm);
- leaching fraction = 20% of applied irrigation water.

Soil hydraulic properties presented in Table 2 are defined below. Parameter units are provided in the table.

depth	soil profile thickness
psi	initial soil matric potential
thetas	soil water content at saturation
psie	matrix potential at saturation (air entry pressure)
b	minus the slope of the straight line approximating the water retention curve on a straight line plot (b ranges from 2 in sandy soils to 25 in clays)
Ks	hydraulic conductivity at field saturation

Table 2 Soil hydraulic properties used in SWIM modelling

Soil	depth (m)	psi (cm)	thetas	psie (cm)	b	Ks (cm/h)	Irrig. (mm/d)	Evap. (mm/d)
Irrig. Torrifluvient with rhodes grass	20	-300	0.2	-20	6	8	6	4.8
Torrifluvient with acacia arenacia	20	-2000	0.2	-20	6	8		6
Torrifluvient without vegetation	20	-2000	0.2	-20	6	8		6
Irrig . Torriorthent with rhodes grass	20	-300	0.15	-10	5	25	6	4.8
Torriorthent with acacia arenacia	20	-2000	0.15	-10	5	25		6
Torriorthent without vegetation	20	-2000	0.15	-10	5	25		6
Gypsiorthid with acacia arenacia	20	-2000	0.5	-15	5	25		6
Gypsiorthid without vegetation	20	-2000	0.5	-15	5	25		6

Table 3 Vegetation characteristics used in SWIM modelling

Soil	Min. Xylem pot (m)	Root depth constant (cm)	Max. root length density (cm/cm^3)	Max. fraction of PET (%)	Simulation duration (days)	Time step (days)
Irrig. Torrifluvient with rhodes grass	-150	30	3	.8	1825	1
Torrifluvient with acacia arenacia	-150	100	2	.6	4906	1
Torrifluvient without vegetation					4906	1
Irrig. Torriorthent with rhodes grass	-150	30	3	.8	1825	1
Torriorthent with acacia arenacia	-150	100	2	.6	4906	1
Torriorthent without vegetation					4906	1
Gypsiorthid with acacia arenacia	-150	100	2	.6	4906	1
Gypsiorthid without vegetation					4906	1

To the authors knowledge no studies of these vegetation characteristics have been undertaken in Oman. The values above are estimates based on similar plant types and visual field observations only.

SWIM provides a soil water balance for a particular soil profile and shows how this changes over time in response to infiltration and evapotranspiration. The water balance aspect of most interest here is the amount of profile drainage for different soils under irrigated and non irrigated conditions. It is not possible to provide rigorous calibrations for particular soil profiles because there are no lysimeter data or detailed moisture profiles available. Nevertheless, since the simulations are based upon extensive measurements of water content for each soil type, qualitative comparisons of profile drainage are considered to be a useful indication of relative recharge potential. Simulated profile drainage (recharge) can be compared with observation bore hydrograph responses for particular soils, under irrigated and non irrigated conditions, to provide a check on model predictions.

Irrigated simulations were conducted over a period of five years using recorded daily rainfall and estimated irrigation applications of 6 mm/day. After initial adjustment, these profiles were found to be quite stable. Non irrigated simulations were run for approximately fourteen years to gain more insight into the impact of wet and dry periods on profile drainage.

DRAINAGE ESTIMATES FOR IRRIGATED AND NON IRRIGATED CONDITIONS

The downward movement of water through the unsaturated zone depends upon the water content. As the water content drops the hydraulic conductivity will reduce to the point where downward movement is imperceptible on a time scale of days. If we consider a simple case where flow can be treated as "piston flow", i.e. longitudinal dispersion and preferential pathways can be ignored, then the travel time of water through the unsaturated zone depends on the water content of the zone and the average flow rate.

For example, if a soil has a water content of 200 mm/m depth and receives an annual recharge of 200 mm, the downward travel time of water will be 1 m/year. If the water table is at a depth of 10 m, it will take ten years for water leaving the root zone to reach the water table, under these conditions.

Now consider an unsaturated zone which has a water content close to field capacity, perhaps sustained by regular irrigation. If at a particular moment, an additional quantity of water is added in excess of the water holding capacity of the root zone, this addition increases the water content in the uppermost part of the zone, which also increases the hydraulic conductivity. As a result the previous water is pushed downward and because of flux convergence, is compressed which increases the water content in this part and so on.

This "compaction" moves down at a speed which depends on the hydraulic conductivity of the water in the "compacted state" and may reach the water table quite quickly, depending upon the depth to the water table. The response time is much shorter than the transit time. What actually happens is that the whole water column is displaced downwards and the water table receives an amount of water equal to that added from the root zone. A prerequisite for this process is a flux of surplus water in excess of the water holding capacity of the root zone.

Provisional drainage estimates derived from the SWIM modelling are presented in Table 4 and provide a first approximation of the relative amounts of drainage that might be expected under irrigated and non irrigated conditions.

These simulations do not allow for surface ponding which will enhance infiltration, or surface sealing effects which might reduce it, although these process can be included later if considered necessary and where data permits. The comments below focus on the modelling results for the Torrifluvients which are the major soil sub group, but the observations are essentially the same for the torriorthents and gypsiorthids. Some aspects of particular interest are picked up in the following discussion.

Table 4 Provisional drainage estimates

Soil	Simulation duration (days)	Mean annual irrigation (mm/yr)	Mean annual drainage (mm/yr)	Mean annual leaching fraction (mm/yr)
A Irrig. Torrifluvient with rhodes grass	1825	2190	510	440
B Torrifluvient with acacia arenacia	4906		4	
C Torrifluvient without vegetation	4906			
D Irrig. Torriorthent with rhodes grass	1825	2190	520	440
E Torriorthentwith acacia arenacia	4906		1.5	
F Torriorthent without vegetation	4906		2	
G Gypsiorthid with acacia arenacia	4906		5	
H Gypsiorthid without vegetation	4906		6	

Note: The difference between mean annual drainage and mean annual leaching fraction provides an indication of the amount of rainfall that can infiltrate under ideal conditions.

A Torrifluvient: irrigated rhodes grass with 20% leaching

The simulated moisture profile was found to be quite stable and is sustained by irrigation. Leaching occurs as a semi-continuous drainage to the water table. Occasional rainfall events exceed the water holding capacity of the root zone and create pronounced moisture bulges on the background leaching profile. Under ideal conditions most rainfall which infiltrates beyond the root zone in this profile is likely to be transmitted rapidly to the water table by piston flow.

It is postulated here that this is the explanation for the rapid direct hydrograph response to precipitation observed in the irrigation areas. Under ideal conditions very high infiltration and recharge could occur in response to rainfall. In reality the variation in controlling factors such as irrigation intensity, area irrigated, canopy interception etc. will generally tend to reduce infiltration and recharge

B Torrifluvient: non irrigated with acacia arenacia vegetation

Under these conditions, the simulated soil profile gradually drains towards a much lower water content with very low vertical hydraulic conductivity. Despite the high, saturated vertical hydraulic conductivity, rainfall infiltration is efficiently withdrawn by soil evaporation and the plant root system. Very little rainfall bypasses the root zone except for major events and rainfall recharge appears to be very low. The sub soil will tend to be saline due to salt concentration by plant water extraction and soil water evaporation.

C Torrifluvient: non irrigated without vegetation

This soil moisture profile is quite interesting. Modelling suggests that, where there is no vegetation, the high, vertical hydraulic conductivity of all these soils enables some rainfall to infiltrate beyond the depth of the soil evaporation zone and down to the water table. However the soil water content is quite low and consequently the vertical hydraulic conductivity is very low also. It follows that downward movement and drainage will be very slow, unless preferential pathways are present and persist at depth.

DISCUSSION

The preliminary unsaturated zone modelling described above provides considerable further insight into the nature of infiltration and recharge under irrigated and non irrigated conditions on the Batinah coastal plain. However the initial results must be treated with caution because there are many factors which have not been adequately considered in this idealised and simplified approach. These factors include surface crusting, runoff, ponding, vapour flow, soil layering effects and irrigation management. Another aspect that has not been considered and which may be significant is the effect of increased humidity (and reduced evaporation) on infiltration during rainfall periods. This factor may be quite important particularly for more permeable soils. Continuous records of near surface humidity are required to evaluate this process.

Irrigated areas

Modelling indicates that under irrigated conditions where high unsaturated zone water contents prevail, rainfall infiltration can produce a pulse which is rapidly transmitted to the water table by piston flow. The existence of this process is supported by the observed rapid response to rainfall recorded on observation well hydrographs. Anomalous irrigation applications may produce a similar response. Modelling also indicates that small infiltrations of 10 mm and less can activate the piston flow process. It is therefore tentatively concluded that rainfall recharge on irrigated areas of the coastal plain is a significant recharge process.

Because of the wide variation in surface and subsurface conditions it is not realistic to accurately predict the amount of rainfall recharge by one dimensional modelling. The observation well hydrograph response provides a better gauge, because it effectively integrates the variability in unsaturated zone processes and surface conditions. The hydrograph response within the irrigated coastal plain area is surprisingly uniform, which implies that hydraulic characteristics and fluxes are also reasonably consistent. This apparent consistency is considered to reflect the concurrence of source material (primarily ophiolite and limestone), depositional processes and landuse pattern.

Periodic rainfall recharge is a small flux component compared to the essential, on going contribution of leaching. Consequently the magnitude and chemical composition of the leaching fraction will largely determine the chemical composition of the shallow groundwater except near major wadis.

Non irrigated areas

Modelling indicates that the situation for non irrigated areas in the central and southern plain is quite different. Under non irrigated conditions, drainage from the soil profile is likely to be very small, because the water content will generally be much lower, resulting in very low vertical hydraulic conductivity.

The predominant soils in the non irrigated areas are gypsiorthids and torriorthents gypsiorthids. Gypsiorthids may have quite high water retention differences and are capable of providing considerable drainage, as much or more than the Torrifluvients. However the presence of a diagnostic gypsum or carbonate horizon may be a major impediment to drainage. Torriorthents are frequently very gravely and hold less water. The simulations suggest that drainage from the torriorthents (Table 4) is very low at about 1-2% of annual precipitation under vegetated or non vegetated conditions. Drainage from the gypsiorthids on the other hand, may be more significant at about 5% of annual precipitation.

Preferential pathways may be significant but field inspections to date have not revealed well developed preferential pathways which extend throughout the profile. Fingering may occur in some of the coarse sand units, but again this has not been observed. The role of temporary ponding along minor depressions warrants further consideration.

The central and southern plain areas mostly comprise gently undulating surfaces with extensive drainage networks which are periodically activated by rainfall on the plain. Infiltration is unlikely to be uniform within this setting, but instead is likely to be concentrated at favourable locations along active drainage lines. Here infiltration rates may be substantially higher, due to frequent reworking of the surface material, by essentially the same processes that control surface characteristics within major active wadis. Ponding of runoff, effected by rise and fall of stage, in these minor runoff channels, may result in significant local recharge. This has not been simulated.

It was tentatively proposed by Lakey et al (1995), that recharge derived from delayed direct recharge on the central and southern plain was responsible for the lagged cyclic fluctuations evident on well hydrographs for this zone. This hypothesis is not supported by the unsaturated zone modelling which suggests that infiltration from rainfall events under vegetated and non vegetated conditions, is either removed by soil evaporation and plant roots, or marginally increases the soil moisture content with no significant effect on drainage. This is because the soil profile in an arid climate gradually drains to a very low moisture content during prolonged periods without precipitation and can easily accept most rainfall infiltration inputs without exceeding the soil water holding capacity.

The effect of periodic infiltration in these dry soil profiles is not seen at the water table unless preferential pathways are well developed. The absence of any direct hydrograph response to rainfall implies that these pathways are not well developed. Modelling indicates that a very slow and continuous seepage to the water table occurs. The travel time for soil water in these profiles is likely to be tens of years, depending upon depth to water table. Under these conditions tritium is unlikely to be preserved, but this does not therefore infer that the aquifers are not in receipt of modern recharge as has been suggested.

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