WSTA Sixth Gulf WATER Conference
In concurrence with
Second Symposium on Water Use Conservation
in the Kingdom of Saudi Arabia

The Ministry of Water
Kingdom of Saudi Arabia

Water Science and Technology
Association (WSTA)

Secretariat
General - GCC

CONFERENCE PROCEEDINGS VOL. I

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8 - 12 March 2003
Riyadh, Kingdom of Saudi Arabia

Under the Patronage of
H.R.H Prince ABDULAH BIN ABDULAZIZ AL SAUD
Crown Prince, Deputy Prime Minister and Head of the National Guard

WSTA Sixth Gulf Water Conference

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Second Symposium on Water Use Conservation in the Kingdom of Saudi Arabia

"Water in the GCC...Towards Sustainable Development"

8-12 March, 2003

Riyadh, Kingdom of Saudi Arabia

CONFERENCE PROCEEDINGS
Vol. I

- **Conference/ Symposium Organizers**
  - The Ministry of Water, Kingdom of Saudi Arabia
  - The Water Science and Technology Association (WSTA)
  - The Secretariat General of The Cooperation Council (GCC) for the Arab States of the Gulf.

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  - Arab Organization for Agricultural Development (AOAD)
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  - Islamic Organization for Education, Science, and Culture (ISESCO)
  - European Desalination Society (EDS)
  - International Desalination Association (IDA)

WSTA Sixth Gulf Water Conference

In concurrence with

Second Symposium on Water Use Rationalization in the Kingdom

" Water in The GCC... Towards Sustainable Development"

8-12 March, Riyadh, Kingdom of Saudi Arabia

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INTRODUCTION

In the last three decades, the GCC countries have experienced an accelerated social, agricultural, and industrial development growth, which was associated with substantial increased in water demands. During this period GCC countries efforts were concentrated principally on supply management to meet the spiraling water requirements, where great efforts have been made in developing additional water sources and augmenting their conventional and non-conventional water supply. These efforts were manifested by the extensive installation of desalination plants, expansion in wastewater reuse, dams constructions capture, store, and utilize surface runoff, as well as increasing groundwater abstraction, which have led in most of the cases to these resources overexploitation. On the other hand, demand management, efficient allocation, conservation, and protection have not taken much attention and emphasis in the water management programs in these countries. This have led to the emergence of many unsustainable water uses and conditions, particularly, low water use efficiently, growing of both water demands and per capita water use, increasing cost of water production and distribution, deterioration of water quality and land productivity, in addition to a wide spectrum of general and local water problems. The situation was aggravated by the lack of comprehensive long-term water policies and strategies that are bases on supply demand considerations in most of the GCC countries, and was further compounded by the institutional weakness and multiplication and overlap of water agencies, and lack of coordination between them as well as with land, agricultural, and housing agencies, and inadequate technical and technological capabilities. All these problems have been materialized in a substantial water deficit and a critical water situation in most of the GCC countries. If current practices and trends continue, it is anticipated that the water deficit will escalate, leading to sharp water shortages and will be accompanied by an increase in stalinization and pollution levels, rendering many aquifers and agricultural lands unusable, eventually placing the GCC countries in a water crises, which will have socio-economic and environmental repercussions on development and progress and will make the water problem as one of the main development constraints in these countries.

Achieving sustainable development in the GCC countries should be based on the principles of sustainable resources development, and be centered around removing sustainability constraints, demand management and augmentation of supplies by controlling waste, improving water use efficiency, and reuse and recycling, and the broader application of modern technology in the fields of water, agriculture, municipality, and industry. Only such actions would achieve a reasonable degree of water and environmental balance and would minimize the water gap in the GCC countries.

The sixth gulf conference is held in Concurrence with the second symposium on water conservation in Kingdom of Saudi Arabia in cooperation with Water Science and Technology Association (WSTA) in Bahrain, Ministry of water in Saudi Arabia and in cooperation with the secretary of the GCC under the theme " Water in the GCC towards sustainable Development".

The holding of this scientific event is considered an opportunity that gathering experts, scientists and specialists in all fields of water science for exchange of Ideas,

views and experiments that will augment the GCC states to face up to the challenges of lack and limitation of water resource.
Eighty scientific papers will be presented in this conference during eighteen sessions in addition to two open discussion sessions dealing with the following:

1. Integrated Water Resources Management Policies & Strategies
2. Surface & Groundwater
3. Desalinated Water
4. Domestic Wastewater
5. Irrigation Water Management
6. Domestic Water Management
7. Efficient Water Conservation Techniques & Tools

The sixth WSTA conference and the secand symposium are considered also as a GCC participation in the occasion of UNESCO (2003 The International Year of Fresh water).

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Vice Minister
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Kingdom of Saudi Arabia

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WSTA Sixth Gulf WATER Conference
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in the Kingdom of Saudi Arabia

Integrated Water Resources Management in Relation to Capacity Building

Dr. Abdulla A. Ahmed (Sudan)

Integrated Water Recourses Management In Relation to Capacity Building

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Abstract

In recent years the subject of sustainable development has gained substantial evidence among water resources professionals. Proper water resources planning and management requires more efforts to be made to develop methodologies that encompass both quantitative and qualitative aspects of water resources management. However, this goal cannot be achieved unless accompanied by strategic well planned capacity building supported by appropriate technical education and training.

The present paper describes, in brief, the Sudanese experience taking into consideration policies, economic, social, education, and training aspects related to water resources. Lack of coordination between institutions working in the field of water resources is pointed out. Further, poor and weak human resources utilization is discussed. The impact of irrigation scheme design on irrigation water management is overviewed in connection to water resources management. The paper concludes that integrated water resources management and develpoment, is the correct and best way to handle the valuable and limited water resources within Sudan and the Nile Basin countries in general. It also concludes that capacity building is a basic component to set up any national and/or regional action plans regarding the management and develpomnent of water resources.

1- Introduction

Integrated development of water resources is important for the welfare of any society, their economy and prosperity. Moreover, it is very essential for the environment conservation. For many years, the term water resources management refers specifically to the supply aspects. Hence, developing water resources means adequate satisfaction of needs. However, the demand side emerged as an equally important, but it is even more complex. Without effective demand management with supply aspects taken into consideration, the main goal of efficient management cannot be reached, especially when related to water scarcity. Historically up to recent years the common belief in Sudan was that the water resources are exceeding the needs. However, experience of the last two decades has showed that water shortage and scarcity were dominant and the country ran into food security problems. This has provided an opportunity of re-thinking basic approaches to solve and manage water problems, as water likes any economic resources has become scarce.

Nowadays " Food Security " is a worrying element to most governments; one third of the world population is leading a very bad life and lacking food. There is increasing evidence and recognition that what is needed for sustainable development, even more than natural resources and physical capital, is for people to be effective and productive. Investment in human capital is what really matters especially in the developing countries and the Nile Basin is not exceptional.

This paper emphasizes on the issue of human resources and institutional development. Therfore, the gap in education, training and coordination between the different institutions working in the field of water resources management and development should be bridged. The Nile Basin countries should consider a regional approach for their common water resources development and utilization, seriously and in a practical manner. Sudan, as one of the riparian countries that confines more than 60% of the Nile Basin and contributes reasonable amount to its total flow, should consider the regional approach. Furthermore, Sudan should call with others for common understanding for better utilization of the Nile Basin water resources for the benefit of all.

2-Planning and Policies

Policies are believed to be for longer period compared to planning. Policies however can never be entirely separated from the reality in which it operates. Moreover there will always be external constraints on effective policy, even with better information and coordination. Hence information and coordination although are desirable this requirement explains why water policy and planning has been deficient. Planning is a forward –looking process that allows us to consider where are we now; where we want to be; and the best ways to get there. Most of the African countries, including the Nile Basin ones, are far away from that "Concept"? Because the process of strategic planning facilitates communication and participation, accommodates divergent interest and values, fosters wise and analytic decision-making, and promotes successful implementation.

Recently, the Government of Sudan has adopted a structural adjustment programme and a free oriented economic policy consists of liberalization of trade, removal of subsidies, reduction in government expenditure and privatization of public enterprises. This economical policy has a considerable impact on the country especially the social side and its influence on the water sector in many aspects is clear and noticeable.

The development of water resources cannot be seen in isolation from the overall political, economical and social development. Therefore, accommodating social, economical and political issues in water resources development projects is very important and often determines success or failure of these projects. Fig (1) shows the interrelation and complex situation of the water resources management in Sudan. Experiences showed how difficult to manage water resources using such a fragmented setup shown in Fig (1), specially when considering coordination, not only between the different bodies but within the same institution. Therefore, unless the Sudan Government consolidates these bodies in one central body to deal with water resources development and management in an integrated manner, the situation will not improve.

The Minister of Irrigation and Water Resources has been advocating to gather the different water resources identifies under one Umbrella. In 1995, the body managing groundwater and wadis was put under the direct responsibility of the Ministry. Recently in 1999, a National Council for Water Resources was formed headed by the Minister of Irrigation and major suppliers and users as members (from Central and State Governments). The objective of the council is to formulate the general policies and outlines of water resources development and management for the whole country and to coordinate between the State Governments and the Central Government.

In general, many water resources management projects, although technically feasible, have failed to benefit the target group and to be sustainable in the long run due to the lack of proper operation and maintenance (O&M). This was not only due to the shortage in finance, but was also due to social impacts i.e. the involvement of the local community and their benefit from such project was not justifiable for the farmers, since the formulation of the project in the first place.

3-Sudan Water Resources

According to ACSAD [1] Sudan ranks as number "Seven" among the Arab countries after Egypt and before Oman in per capita water availability $817m^3$ per person, for the year 2000. Projection for Sudan per capita water availability, given by the same [1], is at about $486m^3$ for the year 2025; i.e. Sudan in spite of its vast fertile land and different sources of water has limited water resources and a gloomy future.
Sudan's surface water and groundwater resources are shared with neighbouring countries. The Nile, the main resource, is shared between 10 countries. Non - Nilotic seasonal streams (Wadis), e.g. Gash and Baraka in the East, are shared with Eritrea and Azum and Howar streams in the West are shared with Chad. Groundwater (The Nubian sandstone aquifer) is shared with Chad, Libya and Egypt. Rainfall is seasonal and is usually concentrated in a short season from (July to September). The annual amount of rainfall in Sudan is relatively large (~1000 Billion m^3). However, it is characterized by its notorious; erratic, temporal and spatial distribution. More than 50% of Sudan area is lying north of latitude 14° N, where rainfall is less than 200mm/year. Therefore, the rainfed cultivation is difficult in this zone.
About 30% of Sudan area is south of latitude 10° N, where the annual rainfall exceeds 700 mm, the most wet area in Sudan. Unfortunately, it is very difficult to cultivate any crop in this zone, due to the swamp area and the tes-tis fly and other reasons. What is left? The Central area, about 20%, where rainfed cultivation is possible. However, it faces considerable difficulties, and the crop productivity is too low e.g. 0.5 – 1.0 ton/ ha for sorghum, compared to 3.0 – 6.0 tons/ ha in the irrigated schemes. In the zone North 10° N certain measures can be taken to make use of such huge water resources, e.g. water harvesting and water spreading techniques. The latter requires well-built institutions and personnel capacities, beside the availability of the capital and the proper technology and know how.
The total internally produced water resources in Sudan are estimated at 36 Billion m^3 [2], (20.5 from the Nile, 5.4 from non-Nilotic streams, 4.1 renewable groundwater and 6.0 expected share from swamps reclamation). The irrigable area in Sudan amount up to 100 Billion ha, which requires more than 500 Billion m^3 of water to have reasonable crop productivity. Therefore, water is the limiting factor for the country development and prosperity.

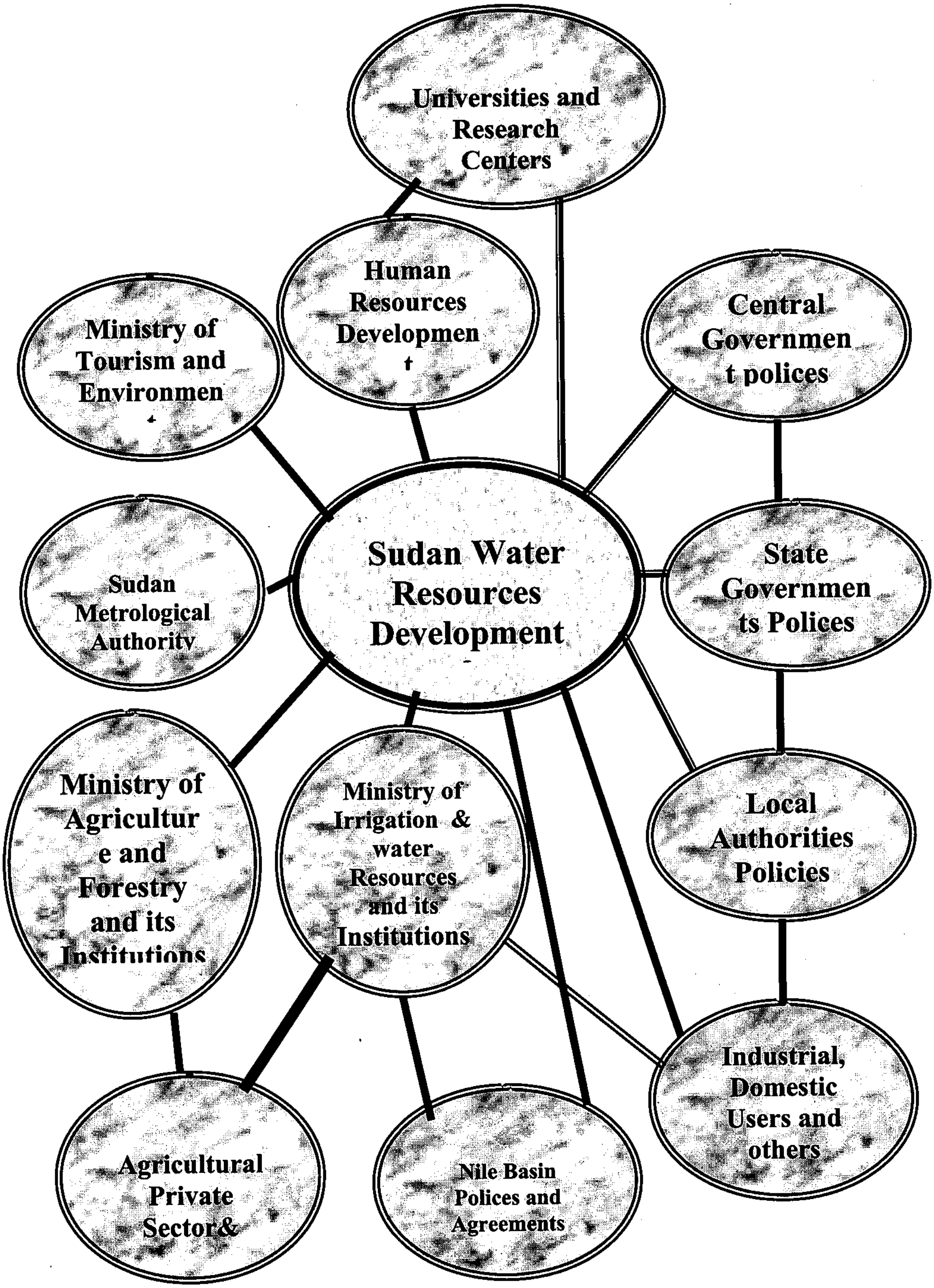

Fig (1) Different bodies dealing with Sudan Water Resources

4-Capacity Building

Capacity building has been widely accepted as an important component for sustainable development. Capacity building consists of three basic, interrelated elements:

- i- Creating an enabling environment with appropriate policy and legal frameworks;
- ii- Institutional development, including the development of sector organizations, as well as that of community participation; and
- iii- Human resources development and strengthening of managerial system.

Experience has shown that institutional weakness and malfunction are major cause of ineffective and unattainable water services. Pressure for improved local delivery of water services suggests that institutional capacity should be developed to be more demand responsive. The need to manage the overall water resources coherently and efficiently and facilitate allocation of water among all users, suggests a need for implementation of integrated strategic planning. Demand driven management requires the development of water related institutions to appropriate levels, taking into account the need for integration with land–use management.

A proposed first step is the development of long-term strategies for water sector capacity building at the regional level. It must be recognized that each country has specific characteristics and requirements to its water sector and resources situation and institutional framework.

5. Education & Training

In 1989, Khartoum University was the only institution graduated Civil Engineers in Sudan (those who work as Irrigation Engineers latter) [3]. Nowadays, the number of universities in Sudan exceeds 26 universities beside many other colleges most of them graduate Civil Engineers. Furthermore, Irrigation Institute was established in the mid Nineties in the Gezira University. Although, it is still working at the M.Sc level, i.e. postgraduates' studies, the institute is planning to open undergraduate studies of irrigation soon, which is a step in the right direction. Such efforts should be supported firmly by the Government and the organizations concerned.

There is no doubt that the highest priority today is to attempt to re-establish the discipline, that has so sadly deteriorated in our irrigation schemes management, which causes crops production to decrease. Here, there is a great need for training programmes at all levels. The primary need is to teach the elements of management including budgeting, financial control, stores accounting, personnel management, and in some cases, procurement and marketing. All these beside, the main subject (the technical side), the irrigation and agricultural management and development. Definitely, such programmes will lead to efficient uses of water and land resources. To carry such a program of education and training, capacity building is required for both the institutions and individuals. Therefore, management training calls for a regional and international efforts. Many countries have become locked into a well-established irrigation bureaucracy, and therefore tend to train new management recruits in out molded ways. International exposure is an important ingredient in any senior management-training programme. UNESCO Chair in Water Resources, Sudan, as one of the institutions working in such an important field tries to establish a training programme courses aiming at better utilization of water resources in collaboration with the relevant institutions, e.g. universities, Ministry of Irrigation, ... etc. To achieve its goals, the Chair adopted a regional and multidisciplinary approach.

In the Nile Basin countries a pronounced need exits for novel training methods for integrated water resources management and planning, as well as to further promote training on community, participation approaches for water supply, sanitation and irrigation institutions. These concepts should be included in the training and education curricula for related professions in the water sector, specifically at the level of university and polytechnic education. Moreover the following important points should be considered:

- Management skills training should be extended to the levels of local institutions and communities.
- Training activities should be better geared toward functions and objectives of the institutions in the water sector.
- Education and training institutes should be mobilized wherever possible and used as instruments to implement capacity building in water resources planning and management.

It is believed that the phenomenon of the shortage in the technical issues may be a common problem to the developing countries and the Nile Basin ones are not exceptional, in which there are many institutes for higher education without any planning or strategy for the actual needs of the society from the different specialization. One feels that Nile Basin countries people usually deviate towards higher certificate rather than the actual needs of their societies. This can be attributed to their belief that the government must employ graduates. Hence, many graduates are working in posts totally different from their specialization and government institutions are overstaffed without leading to increase in production. Therefore, education and training processes should be tied to the development programme and all jobs should be given just fair weights by closing the existing huge gap in payments, particularly in the field of irrigation.

One of the learning mechanisms is the media, since information in general plays an important role in decision-making and public awareness. Therefore, the management of information is an integral part of the decision-making and involving partners at all levels in a continuous process. Professionals through media and other means should under take initiative directed towards politicians, decision-makers and the general public to raise awareness of the finite and fragile character of water resources. This will create better understanding and common ground for decision-making, hence, leading to effective and efficient policies and planning of water resources.

6. Nile Basin Capacities Building Network for River Engineering (NBCBN-RE).

Realizing the importance of capacity building for the Nile Basin countries to utilize and manage their valuable water resources in an efficient and effective manner, the Egyptian Government, supported by the Netherlands through the technical assistance of IHE – Delft and ITC – Enschede, agreed to establish a Regional Training Center aiming at the following, [4]:

i. To strengthen the human resources and institutional capacity of the Nilotic States to manage water resources in the Nile River basin in an effective and environmentally sound way.
ii. To strength the human resources development capacity and research capacity in River Engineering.
iii. To increase the co-operation between training and research institutes in the Nile Riparian States so as to, create mutual understanding and build confidence among scientists and politicians from different countries sharing the same resources.

The mechanism through which the above objectives can be achieved is summarized as follows, Fig. 2:

- Regional Training Center as focal center for capacity building with up to date facilities in HRI - Egypt.
- Establishing Center of Excellence in each of the riparian countries with an objective to strengthen capacity building in specific fields related to better utilization of Nile water resources e.g. the recently established Center of Excellence in River Morphology in Sudan (hosted by the UNESCO Chair in Water Resources) and the Center of Excellence in Egypt for GIS and Hydraulic Modelling (hosted by HRI).
- Holding workshops on topics related to integrated water resources management in the Nile Basin countries, aiming at bringing professionals and scientists together for exchanging experience and ideas.

- Holding short courses (2 weeks) in pre-determined topics related to the above capacity building objectives on rotational basis within the Nile Basin countries.

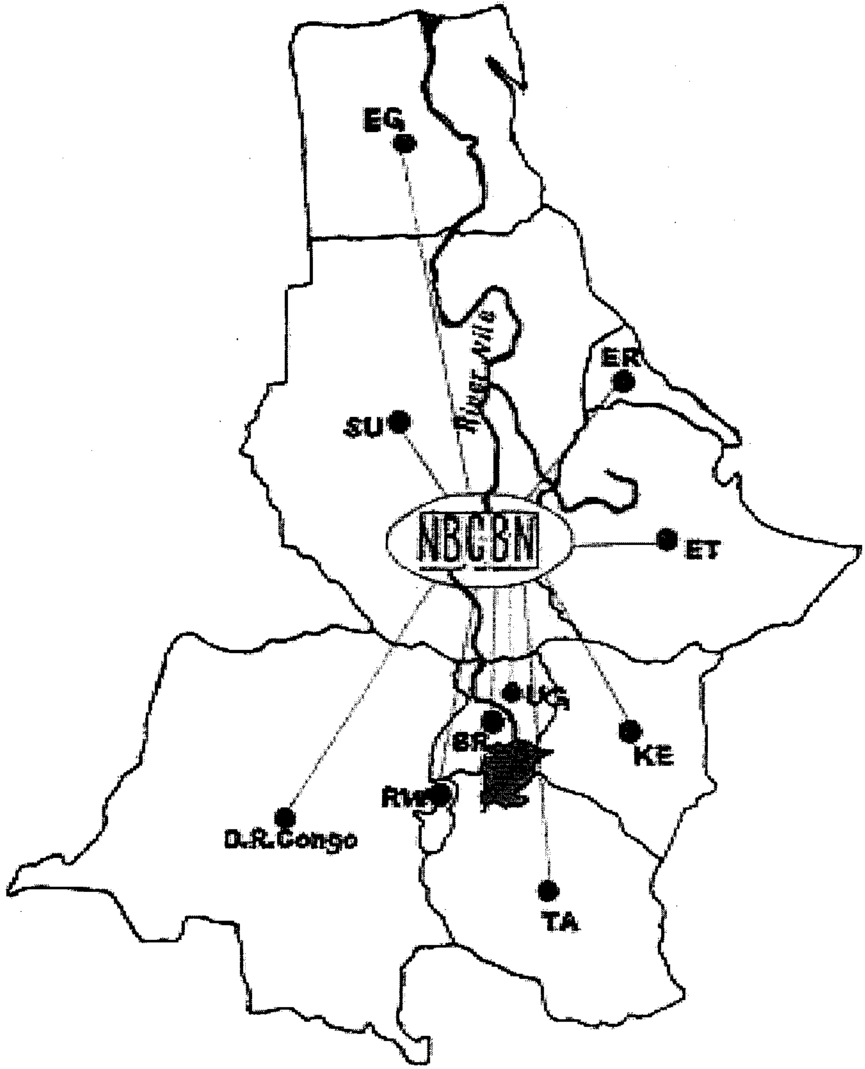

Fig. 2 The Nile Basin Capacity Building Network for River Engineering

7.Nile Basin Initiative (NBI) and Friend/ Nile Project

Several plans and activities have taken place attempting to create cooperative projects and programs for the Nile Basin countries. We believe that all of them aim to achieve sustainable socio-economic development through the equitable utilization of, and benefit from, the common Nile Basin water resources. Both NBI and the Friend / Nile project [5, 6] aim at enhancing an integrated management of the water resources of the Nile and its tributaries through enhanced cooperation amongst the Nile countries. This will ultimately contribute to meet the basic needs of safe and clean water supply, as well as to promote sustainable development of the region. The Author of this paper believes that the NBI and the Friend/ Nile project, beside their overall goal of establishing and maintaining regional database and networking activities are succeeded to build the capacity of the involved institutions, and the personnel of the participating countries. Therefore, better understanding and cooperation will be generated for effective and efficient utilization of the Nile Basin water resources.

8.Towards Integrated Approach for Irrigation projects

Agriculture is by far the largest water user in the Nile Basin (80%-90%), and is of great economic and social importance. Irrigated agriculture is mostly present in the northern part of the Nile Basin; rainfed agriculture prevails in the south and eastern parts. However, in the Nile Basin countries, as in many developing countries irrigation development takes place in isolated steps, i.e. the feasibility study, the planning, the design and construction. Preparation for the operation and maintenance (O&M) of the completed projects are often not included. Therefore integrated approach in irrigation development, with attention not only for design and construction but also simultaneously to operation and maintenance leads to satisfying results. Monitoring of water distribution and the results of agro-economic surveys also contribute to a regular and direct feed back of field information to the O&M staff, the agriculture extension and credit and marketing services. Results might even have further improved if an agronomic component was included in the project (e.g. crop diversification).

The previous benefits cannot be attained unless adequate preparation for field operation staff (by proper training) and farmers to be trained (on–farm) in irrigation practices and the related facilities for good crop production. Consequently, the full benefits of irrigation projects are hardly or seldom achieved.

On the other hand, it is useful to distinguish between two fundamental elements of development and management of water resources for irrigation. The first is concerned with the creation of regulated and guaranteed flow of water and it's delivering to the project area. The second deals with the distribution of this flow throughout the project area, its application to crop root zone and the removal of access water. The integrated approach if adopted in all projects within the Nile Basin countries will lead with other elements to efficient and effective utilization of the water resources.

9.Conclusion and Recommendation

It is clear that the integrated approach of water resources management and development on both the supply and the demand sides is the best way to handle such a valuable resource within the Nile Basin countries. To achieve the goals of efficient and effective use of water resources, capacity building should be a fundamental component of cast and target national and regional action plans. It is found that capacity building means dealing with different components: education, training, and transfer of knowledge research, institutions building and institutional development. The paper concludes with the following important remarks:

- Capacity building is an essential requirement for efficient water resources management. Sudan and Nile Basin countries must give it priority consideration.
- Capacity building should directly reflect needs and overall conditions of the country concerned.
- Capacity building should be a long–term process.
- Capacity building should have short, medium and long–term goals.
- Good communication, exchange of information and extensive interactions between different stakeholders and levels are essential requirements for a good capacity building process.
- Organized systematic plan for water technology transfer from highly developed worldwide sources to the different corresponding sectors inside the Nile Basin region and in each country is high required.
- Coordination and systemic exchange of information between many bodies dealing with water resources within the Nile countries are essential.
- Institutions and human resources capacities should be built through out the Nile Basin countries in a proper and national way to enable them play their expected role, taking into consideration what has been reported in this paper.

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Towards Sustainable Management of the Palestinian Water Resources

Dr. Amjad Aliwei, Anan Jayyousi and Geioff Parkin (UK)

TOWARDS SUSTAINABLE MANAGEMENT OF THE PALESTINIAN WATER RESOURCES

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Abstract

Palestine is among the countries with the scarcest renewable water resources per capita due to both natural and artificial constraints, amounting to only 100 cubic meter per capita per year. This is far below the per capita water resources available in other countries in the Middle East and the World. At present water demand exceeds the available water supply. The gap between water supply and water demand is growing due to population growth, higher standard of living, and the need to expand irrigated agriculture and the industrial activities. This growing gap is calling for the utilization of any additional conventional and non-conventional water resources. This paper aims at:

- Providing a technical outline of the surface and sub-surface water resources of Palestine and water demand issues so that the status of these resources against demand will be identified;
- Using this technical framework as a basis for trying to highlight a possible sustainable scenario for managing water resources in the West Bank and Gaza Strip.

Key words: Water Resources, Palestine, Management, Water Rights

Introduction

Groundwater is the primary source of water for the Palestinians in the West Bank and Gaza Strip. The groundwater resources of Palestine are extracted from aquifers (rocks that are capable to store and transmit water). The West Bank uplands comprise the regional recharge area for the extensive aquifers, which under natural conditions discharged from springs. The surface water in Palestine is mainly the Jordan River in addition to many seasonal wadis.

The development of sustainable water resources issues in Palestine is complex. This is because Israel has imposed new facts on the ground over the long years of Occupation and as a result put the Palestinians resources under great stresses. At present, the development of additional water sources is restricted and based on the approval of the Israelis since Palestinian water rights is still a subject of the results of the final status negotiations. In this context it is foreseen that the stability of the final status agreement on water will only be assured if the Palestinians achieve their water rights (Younger et al, 1998). In addition to the scarcity of the water resource under the political constraints imposed by Israel, the protection of the water resource environment is another constraint that makes it difficult to develop sustainable demands/supply scenarios in Palestine which does not seem to be heading to a clear socio-economic future.

Water Resources In Palestine

Groundwater Basins of Palestine and Israel

Since the partition of Palestine in 1948 (which was instigated by the League of Nations to accommodate the creation of the State of Israel), the water resources of Palestine have been studied and presented according to political boundaries and thus the political interest of the Israelis was dominating many water facts. Subsequently, and following several wars (e.g., 1967, 1973 and 1982 wars and invasions) between the Arabs and the Israelis, the latter put under their control the water resources of the entire region which includes the water resources of the West Bank, Gaza, and some territories from Syria and Lebanon. This situation continued for several decades during which the Israelis imposed strict acts to prevent the Palestinians from developing their water resources. After the creation of Israel and each war and invasion against Arab lands, the Israelis launched major well drilling programmes in support of Israeli settlements and communities.

The above Israeli practices, put them in a position to study in detail the water resources of the entire region and consequently they produced many reports and studies, most of which were released to protect their political interest to control the region's water resources. Therefore, caution should be practiced when considering the Israeli data and figures about the water resources of the region. This is applicable to Table 1 and Figure 1 which summarize the groundwater system in the region (Palestine and Israel). The data of Table 1 and Figure 1 are taken from the Hydrological Service of Israel, HSI (1999). This reference is in Hebrew and the only official reference that is made available to the Palestinians. We are using this reference here just to give an idea about the water resources of the entire region although we have our own reservations about the data presented in the report.

Table 1 show that the Israelis and Palestinians jointly use the following aquifer basins; the Coastal Aquifer Basin, the Western Aquifer Basin and the Northeastern Aquifer Basin. Table 1 reflects the Israeli claim that the overall balance of the basins is negative (-212 MCM/yr) such that the total annual net recharge to the groundwater basins is around 1833 MCM/yr while the annual productivity of the aquifer basins is approximated at 2045 MCM/yr. On the contrary the Israelis in the same report (HSI, 1999) claimed that it is possible to develop huge volumes of water (through many wellfields) in the Tabariya Aquifer Basin. It is important to note that this Basin is on the boundaries between Israel, Jordan and Syria and this Israeli report does not acknowledge this fact.

Table 1
Water Balances for the Groundwater Basins in the Region (MCM/yr) after Hydrological Service of Israel, HSI (1999)*

Basin	Natural Recharge	Return Flow	Abstraction	Spring Discharge	Yield
(1) Coastal	299	136	420	-	420
(2) Western	366	16	399	52	451
(3) Western Galali	194	-	82	51	133
(4) Karmel	39	-	36	6	42
(5) Tabariya	550	-	58	466	524
(6) Eastern and Northeastern	330	-	148	238	386
(7) Nagab and Arabah	55	67	89	-	89
Total	1833	152	1232	813	2045

***Data may be inaccurate and released by the Israelis for political reasons**

Groundwater Resources in The West Bank and Gaza

The West Bank Groundwater Resources

The West Bank is a hilly area, the hills being used for pasture, with elevations varying from 400 m below sea level in the Jordan Valley to 1000 m above sea level in the hills. These mountains have terraced valley flanks and valley floors and used to support subsistence arable cropping and commercial olive cultivation. The rainfall of the West Bank (Husary et al, 1995) is strongly seasonal (October to May) and orographic (700 mm in the mountains and 100 mm in the Jordan Valley). The surface geology of the West Bank is comprised of well fractured and karstified carbonate rocks, both limestone and dolomite. Various geological formations are generally non-covered and show outcrops at the surface. This is true even for the very deep formations. Outcrops appear at the top of hills as a result of strong folding and faulting. Therefore, it is likely that these hills are major recharge zones for the West Bank aquifer systems, especially in the non-developed and non-covered areas. The existing water resources of the West Bank are derived from three groundwater aquifer basins (Figure 1) (Eastern Aquifer Basin, EAB, Western Aquifer Basin, WAB, and Northeastern Aquifer Basin, NAB), a series of springs that emanate from the groundwater. At the present time the groundwater and springs provide essentially all of the consumed water in the West Bank. The yields of the West Bank Aquifer Basins are not certain because of the lack of understanding of the water balance of these basins. The uncertainty of the yields of the three aquifer basins appear in the wide ranges provided for each basin as shown in Table 2.

Table 2
Reported Aquifer Basins Recharge

Aquifer Basin	Recharge Rates (MCM/yr)
Eastern	100-172
Northeastern	130-200
Western	335-380
Total	565-752

Gaza Strip Groundwater Resources

Groundwater in Gaza Strip, which accounts for almost 98 percent of the current use, is the only significant source of water for the people of Gaza Strip; the remaining supplies are purchased from the Israeli water company Mekorot[1]. Surface water that might be available from Wadi Gaza is diverted outside of the area.

The Gaza coastal aquifer consists of sand, sandstone, poorly consolidated shelly sandstone and pebbles of Pleistocene age. Semi-impervious silty-clayey layers are scattered in the aquifer. Gaza coastal aquifer is shallow with depths to water table range from 70 m in high topographic areas to less than 5 m in the low topographic lands near the coast. The aquifer is highly permeable and porous. The aquifer thickness can reach up to 160 m near the shoreline.

Rainfall is the major source of groundwater replenishment in Gaza. Rainfall either recharges the groundwater or is collected in cisterns and used immediately. Other sources of groundwater replenishment include groundwater flow from the eastern side, infiltration from surface water runoff, pipe leakage, infiltration of untreated wastewater, and return flow irrigation. MOPIC (1996) estimates of the quantity recharged into the Gaza Aquifer from the various sources are summarised in Table 3 below.

Table 3
Groundwater Replenishment for the Coastal Aquifer of Gaza (MOPIC, 1995)

Sources of Return Flow	Estimated Quantity (MCM/yr)	Percent Total (%)
Rainfall	46	41
Groundwater Flow from the East	7	6.3
Surface Water Infiltration	2	1.6
Pipe Leakage	13	11.6
Untreated Wastewater	14	12.5
Irrigation	30	26.8
Total	112	100

Palestinian & Israeli Wells and Springs in the West Bank and Gaza

There are 359 abstraction wells in the West Bank under Palestinian control, mostly private use. The Palestinian wells extract about 62 MCM/yr on average as follows: 31 municipal wells yielding about 16 MCM/yr; 13 West Bank Water Department wells yielding 12 MCM/yr and 315 agricultural wells abstracting 34.5 MCM/yr. There are 36 abstraction wells under the Israeli control. They extract about 42 MCM/yr. Table 4 represents the Palestinian and Israeli wells in the West Bank according to their location in aquifer basin.

Table 4
Abstraction (MCM/yr) of the Palestinian & Israeli Wells
In the West Bank (HIS,1999)

Basin	Palestinian wells		Israeli wells	
	No. of wells	Abstraction	No. of wells	Abstraction
Eastern	129	25.12	28	29.85
North-Eastern	85	16.48	4	9.82
Western	145	20.78	4	2.10
Total	359	62.37	36	41.77

***Raw Data is obtained from the Palestinian Water Authority Database**

There are approximately 300 springs in the West Bank, of which 112 are considered major freshwater springs. The total annual discharges of the major springs are about 60 MCM/yr. However, 50% of the spring discharges are of brackish quality and 50% are of freshwater quality. About 49 MCM/yr of the spring discharges are used for irrigation and 4 MCM/yr are used for municipal and domestic purposes. Israel controls some groups of springs in the West Bank (e.g., Fashkha and Ghwier spring groups) and Ein Gedi groups system that is located outside the West Bank borders. The average yearly amount of discharge is estimated at 103 MCM (including Ein Gedi Springs outside the Greenline).

In the Gaza Strip, the current water resources available to Municipal and Industrial (M&I) sector is 53 MCM/year, of which 48 MCM/year are abstracted from wells in the aquifer of which 1.2 MCM/yr are from private wells and 5 MCM/yr are supplied from Mekorot Israeli water company. The agricultural supply, which is currently 85 MCM/yr, is exclusively supplied from wells in the aquifer. This gives a total abstraction of 133 MCM/yr from an aquifer with an estimated safe yield of 57 MCM/yr.

Surface Water Resources of Palestine

Surface water in the West Bank consists mainly of the Jordan River with its tributaries and Wadi floods in high rainfall years.

Wadis

Surface water flow in wadis is referred to as surface runoff, which depends mainly on quantities and duration of rainfall during the wet season. It was found that surface runoff occurs when rainfall exceeds 50 mm in one day or 70 mm in two consecutive days. The total runoff in the West Bank is estimated at 64 MCM/yr. Different studies on water and wastewater shows that some 20 MCM/yr could be utilised from surface flood water in major wadis by the construction of storage dams in these wadis (MOPIC, 1997).

Wadis in the West Bank are divided into two major groups: eastern wadis and western wadis. Wadis flow from the central mountain towards the Jordan Valley, and contribute to the recharge of shallow aquifers, and the Jordan River. Western wadis flow from the central mountains in a westerly direction towards the Mediterranean Basin. These wadis are of importance for surface water streams, where floods from different wadis coincide together to form major streams which discharge into the Mediterranean Sea.

The Jordan River System

The Jordan River flows from north to south from elevation of 2200 m above mean sea level at mount Hermon to about 395 m below mean sea level at the Dead Sea. The Jordan River passes a straight distance of about 140 km with a river length of about 350 km due to its tortuous path.

In the northern part (from Al-Huleh to the north), the Jordan River is surrounded with high hills. Form Al-Huleh to Lake Tiberias; the Jordan River divides the lands. The slope of the land and accordingly the riverbed is slight and directed toward the south. Much steeper gradients than the Jordan River itself are found in all of its tributaries. The natural flow of the river in the absence of extraction is estimated at 1300 -1800 MCM/yr at the entrance to the Dead Sea.

The catchment area of the Jordan River and Dead Sea basins is about 40,650 km^2. Table 5 shows the areas and rainfall supply of the catchment within the basin. From this Table, it can be seen that although the West Bank has 7% of the total catchment area of the basin, it has 11% of the catchment area with more than 300 mm of annual rainfall. In comparison, the area of Israeli catchment is 19% of the total catchment area of the basin, but Israel has only 12% of the catchment with rainfall more than 300 mm/yr. This is because 4,780 km^2 of the Israeli catchment are located in Wadi Araba where rainfall is about 50 mm/yr (GTZ, 1996).

Different measures (like draining of Huleh Lake and transferring saline/brackish water of salty springs to Lower Jordan discharging of industrial wastewater) have been implemented on the Jordan River by Israel, which affected its natural flow, deteriorated the environment and adversely impacted the regional ecology.

Israel has been for a long time transferring huge quantities of surface water through the National Water Carrier from Upper Jordan to Negev primary for irrigation purposes. The transferred quantities nearly equal the annual discharge of the three main tributaries of the Jordan River. This is an illegal unilateral action that adversely affects the other riparian rights and embezzles their water.

Table 5
Areas of catchment and Rainfall Supply in the Jordan and Dead Sea Basin (GTZ,1996)

Country	Name of Catchment	Area (Km^2)	Average Annual Rainfall over basin (mm)	Average annual supply from rain (MCM)	Area covered by Isohyets over 300mm (Km^2)
Israel	Upper Jordan	1160	678	786	1160
	Jalout V.	560	441	247	560
	Hebron	1190	122	145	0
	Wadi Araba	4780	50	239	0
	Total	**7690**	**184**	**1417**	**1720**
Syria & Lebanon	Upper Jordan	1580	928	1466	1580
	Yarmouk	5840	395	2307	4532
	Total	**7420**	**508**	**3773**	**6112**
Jordan	Yarmouk	1410	343	483	710
	Ajlun	1250	525	656	1093
	Wadi Zarqa	2960	291	860	1050
	Salt	570	360	206	348
	Madeba	980	306	300	561
	Wadi Wala	2050	201	410	420
	Wadi Mojeb	4460	126	563	430
	Kerak	840	224	189	315

	Wadi Hesa	1750	162	283	250
	Wadi Araba	3020	112	338	200
	Total	**19290**	**222**	**4288**	**5377**
West Bank	Nablus - Jenin	1400	389	545	943
	Jerusalem - Hebron	1350	331	447	695
	Total	**2750**	**361**	**992**	**1638**
Egypt	Wadi Araba	3500	50	175	0
Total		**40650**	—	**10645**	**14847**

Future Palestinian Water Demand

Different estimates have been developed for the future Palestinian water demand. The differences in these estimates resulted from the differences in the assumptions of the future population and the assumed per capita water consumption. In general, water demand in these studies has been divided into two sectors. Those are the Municipal and Industrial water demand (M&I) and the agricultural water demand.

M&I Water Demand

The historic water demand in the West Bank and Gaza Strip has been artificially constrained by non-market forces. As a result they cannot be used to forecast future demands. In fact, on the basis of various world and regional water consumption levels, the present magnitude of unsatisfied demand in the planning area nearly surpasses current supply quantities (PWA, 1999). Thus, it is necessary to plan for and develop more equitable, yet feasible, future water consumption rates and supply capabilities for needed social and economic development.

The total water use by the domestic and municipal sectors in the West Bank and Gaza Strip during 1999 was estimated to be 101.3 MCM. An amount of approximately 52.3 MCM was used in the West Bank, whereas a total of approximately 49 MCM was used in Gaza Strip.

Population Projections

Population increase is the fundamental parameter affecting future water needs. This determines not only domestic demand, but also agricultural/livestock demand (to feed the population) and commercial/ industrial demand (to provide an economy to support the economic development of the population). The assessment of future population has been carried out using the Palestinian Center Bureau of Statistic (PCBS) census results as a base for the end of the year 1997 since it is the only available census and then applying population growth rates. The assumed population growth rate ranges from 3.5% for the year 2000 to 2005, 3% for 2005 to 2010, and 2.5% thereafter.

These growth rates have been adopted following a review of previous studies and closely follow the MOPIC guidelines. The short term rates are very similar to the 3.7% experienced in Jordan in 1998, which is a country with similar economic and cultural conditions.

In addition to the natural growth of the base population, allowances have also been made for returnees, who are defined as those Palestinians displaced to other countries following 1967 and their dependants. Various estimates of the number or returnees have been generally accepted that 500,000 will return as Palestine continues to be established as an autonomous political entity. It is assumed that 80,000 have already returned and that reminder will come in equal annual increments up to 2005 and it is also assumed that the returnees' population will increase at the same rates as the base population. Based on these assumptions the resulting population projections are 3.9, 4.4 and 5.7 millions for the years 2005, 2010 and 2020 respectively.

Future Municipal and Industrial Water Demand

For the future per capita municipal and industrial water demand, target levels are considered. Two target levels are set for domestic water consumption based on "Guidelines on Technologies for Water Supply System in Small Communities", published by the WHO, 1993. These rates are 100 l/c/d, and 150 l/c/d (a minimum and average WHO rates for house connections in small communities), which are to be met with time. Demand rates are estimated based on these projected consumption rates and target overall loss rates. These rates, which are assumed to decrease gradually from the current level, reflect anticipated improvement and expansion of the physical and institutional infrastructure. Other consumption rates including industrial, commercial, and livestock consumption rates are projected as a percentage of the Municipal water demand since no data is available at present on these consumption rates and according to the Water Sector Strategic Planning Study. Based on these target consumption rates and an estimated overall loss rate ranging from 40% to 25% by the year 2020, the estimated municipal and industrial water demand are 406, 460, and 554 MCM/yr for the years 2005, 2010, and 2020 respectively.

Agricultural Water Demand

Available land for irrigation is limited in every Governorate in Palestine, but limitation is particularly severe in Gaza Strip Governorates due to urban pressure, while more land is available readily in the Jordan Valley. The current irrigated land in the West Bank is about 95,000 dunums while the potential irrigable land is about 610,000 dunums. In the Gaza Strip, further expansion of irrigable land even agricultural land is not foreseen as urban pressure that will require more land for building. The irrigable land will in fact decrease.

For future role of irrigated agriculture in the Palestinian economy, it was assumed that expansion in irrigated agriculture mainly aims to satisfy local consumption of traditional irrigated crops (vegetables, melons, oranges and bananas). It was estimated that the average annual consumption of irrigated crops in the West Bank is 272 kg per capita (179 kg vegetables, 40 kg melon and 53 kg oranges and bananas) (GTZ, 1996). Also, it was estimated that the weighted-average production of irrigated agricultural crops is 3,000 kg/dunum. Thus, 0.091 dunum per capita should be irrigated in order to maintain self-sufficiency in traditional irrigated agricultural crops.

With improvements in irrigation and agricultural technologies, average production will increase; accordingly and in order to maintain self-sufficiency in irrigated crops about 0.088du/cap and 0.084 du/cap should be irrigated in the year 2010 and 2020, respectively considering that trade in these crops with nearby countries will be in two directions. Thus, imports and exports will be balanced with neighbouring countries as they share similar water shortages and similar climates. Therefore, there is no need to reduce or increase or adjust irrigated land per capita for trade reasons.

Based on the above assumptions the total agriculture water demand for the years 2000, 2005, 2010 and 2020 are about 224 MCM, 266 MCM, 299 MCM and 353 MCM, respectively.

Future Water Demand and Resources Gap

Based on the above estimates and assumptions, the total water demand for the future is 672, 759 and 907 MCM/yr for the years 2005, 2010, and 2020 respectively. The amount of 907 MCM/yr is about three times the available supply at present but at the same time is not higher than the Palestinian water rights from the renewable sources.

Throughout the Middle East there is a gap between water demand and water supply. In Palestine, this gap is growing even greater than normal since water supply is artificially constrained by the current restrictions effected under the occupation status. This gap, if not bridged, in a timely sustainable manner, will inevitably have serious adverse effects on future Palestinian socio-economic and commercial development. Based on the above estimates, Palestinians should be able to develop an additional amount of 600 Mcm/year from the different resources by the year 2020. The growing gap will be totally dependent on the development options and the action plans to be implemented.

Recommended Management Options

In our case and considering the sustainable yield of the available resources, conventional and non-conventional water resources will have to be mobilized and will account of water with lower quality as far as practical and economic for agricultural use. These resources include:

1. Groundwater resources in the West bank and Gaza Strip. Estimates show that 504 Mcm/year can be a sustainable target from the groundwater resources in the West Bank and 82 Mcm/year from the Gaza aquifer system by the year 2020. These amounts are below the Natural Palestinian water rights in these aquifers.
2. The Jordan River system from which some 100 Mcm/year can be utilized in the West Bank. This amount is below the Palestinian water rights from the Jordan River system according to International water law.
3. Treated wastewater effluents. The estimated amount for the year 2020 from reuse is some 90 Mcm/year, of which 40 mcm/year in the West Bank and 50 Mcm/year in the Gaza Strip.
4. Harvested storm water for aquifer renewal.
5. Desalination and de-nitrification (treatment of the low quality water) especially in the coastal region. Estimates show an amount of 45 Mcm/year of brackish water in the West Bank and some 10 mcm/year in the Gaza Strip.
6. Water importation, desalination of seawater and large scale regional schemes. These large scale projects will cover the rest of the water gap which amounts to some 150 Mcm/year by the year 2020.

Based on preliminary estimates, the utilization of the groundwater resources and the Jordan River system is cheaper than desalination and water imports and the latter two have less security of supply due to political conditions and third party involvement. In view of these facts it is recommended that these only be considered as later developments to serve the water gap in the later stages or are considered as emergency measures if other solutions fail to be implemented.

Conclusions

The main conclusion out of this paper is the fact that the relation between water supply and water demand in Palestine is complex due to the following:

1. The political fact and the uncertainty in the water sector since water issues are delayed to the final status negotiations.
2. The high vulnerability of the different sources to pollution and the direct effect on the sustainable yield of these sources.
3. The effect of the Israeli abstraction rates from the different shared resources on the amount that can be utilized in a sustainable manner especially that the Israeli control and regulation of water demand and abstractions from the groundwater resources and the Jordan River are not governed by the principles of the International Law and all relevant United Nations Resolutions.
4. The high uncertainty of the socio-economic future of Palestine especially the effect of this on the agricultural sector.

Other conclusions and recommendations out of this paper can be summarized into an action plan for the development of additional resources. This action plan include:

1. Continued drilling of production wells at selected locations
2. continued drilling of exploratory and monitoring wells that should be carried out with emphasis on the Kurnub (sandstone) aquifer.
3. Models should be developed to increase understanding of the various aquifers
4. Rehabilitation of existing wells and springs will be undertaken to improve yields
5. Use will be made of brackish water and treated wastewater for agricultural purposes
6. Storm water harvesting will be implemented to improve resources for irrigation and aquifer recharge
7. Emergency measures in the Gaza Strip to produce minimum acceptable domestic water for all in the short term including the provision of bottled water as necessitated.
8. Initiate actions to improve the quality of the Gaza aquifer including an accelerated program to reduce abstraction to the sustainable yield
9. The exploitation of the freshwater lenses will be maximized through the horizantal drain interceptors, skimming wells and scavenger wells in the Gaza Aquifer/

Finally, it should be emphasized that any plan for sustainable development of Palestinian water resources should be dynamic enough to cope with changing conditions in circumstances where the planning authorities do not have full control over the water resources.

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Decision Support system for Efficient Groundwater Management for Irrigation in Arid Regions

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Decision Support System for Efficient Groundwater Management for Irrigation in Arid Regions

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ABSTRACT

Limited groundwater is the major water supply for satisfying different demands specially agriculture in arid regions such as Arabian Gulf countries. Proper management of groundwater resources is important for long-term sustainability of water resources and agriculture developments. This requires effective decision support system based on aquifer characteristics to forecast the short-term and long-term impacts of different water use scenarios for irrigation on groundwater conditions. This helps in adaptation of suitable cropping and irrigation policies for small and large irrigation scheme to avoid unacceptable impacts of groundwater in terms of quality and production. Furthermore, proper irrigation water scheduling and operation results in minimizing water and fuel use and reduction in the costs of irrigation operation. Several water management models were developed for planning groundwater operation and management during the last three decades. But, most of these models do not cover the actual field conditions and they are not dynamic and flexible enough to deal with changing situations. New and original decision support system for groundwater management has been developed. The system consists of two main models namely: groundwater simulation model and dynamic irrigation water management model. This system has been implemented in several agricultural projects in the Kingdom and resulted in significant saving in water and costs of operation and maintenance in addition of increase in agricultural yield. Large scale implementation of such system will result in significant saving in water and energy in addition to improve in agriculture yield.

INTRODUCTION

Saudi Arabia which has limited water resources relies mainly on groundwater for satisfying the agricultural water demands. The area of irrigated agriculture has increased from less than 0.5 million hectares to over than 1.6 hectares in 1999. The irrigation water requirements exceed 90% of total national water demands (Abderrahman et. al. 2000). Improper operation of groundwater in small and large irrigation schemes has resulted in excessive water use and in large unpredicted water level drawdown and deterioration in quality. Significant water losses of about 15-35% of the total irrigation water use have been measured in some large irrigation schemes even with the use of advanced and modern irrigation systems due to the absence of a proper water scheduling (KFUPM/RI, 1991). Proper management of groundwater resources is important for long-term sustainability of water resources and agriculture developments. This requires effective planning of the agricultural schemes in terms of identification of the extent of cultivated areas, types of crops and area of each crop prior to the actual field cultivation. This enables the operators and the management of the agricultural companies in avoiding any future negative impact on groundwater, and helps in achieving sustainability of aquifers and agricultural activities. This will also help in adaptation of suitable cropping and irrigation policies for small and large irrigation. Furthermore, proper irrigation water scheduling and operation results in minimizing water and fuel use and reduction in the costs of irrigation operation.

Conventional groundwater models are used sometimes for simulation of groundwater conditions in irrigation schemes to improve water management. Several crop-water use and scheduling models were developed for planning water delivery and operational management during the last three decades. These models were based on the simulation of processes related to water transfer in soil-plant-atmosphere systems for estimating irrigation demands and setting schedules. A Computerized Irrigation Scheduling Service (CISS) based on calculations of water consumption and field measurements was developed and used in some western states of the U.S.A. (USDI, 1979). The Irrigation Water Requirement System (IWRS) was developed for use with full water supply to obtain maximum yield from irrigated crops (TWDB, 1975). The California Irrigation Management Information System (CIMIS) was developed to provide computerized irrigation scheduling programs for California on the basis of historical and real-time weather data, and to improve water budget scheduling technologies (Snyder et al., 1985). RELREG, a model for real-time irrigation scheduling, was developed by Teixeira et al. [1993] to support the farmer's decision on irrigation doses and timings. A simulation model called CROPWAT (FAO, 1992) was developed by FAO to calculate reference evapotranspiration, crop water requirements, irrigation schedule, and scheme water supply using a climatic database called CLIMWAT. The FAO developed a system called Scheme Irrigation Management System (SIMS) for the operation and management of irrigation systems. Planberg et al. [1996] developed a decision support system for irrigation scheduling at the farm level. Endale and Fippe [1996] stressed the importance of modeling irrigation strategies and scheduling in irrigation districts.

But, there is no decision support system coupling groundwater simulation model with dynamic irrigation demand and scheduling models for effective planning and operation of groundwater in small and large irrigation schemes in arid regions.

A New and original decision support system for groundwater management (DSSGM) has been developed by the water section of KFUPM/RI. The system consists of two main models namely: groundwater simulation model and dynamic irrigation water management.

This paper describes the model development, features, implementation, and benefits for large irrigation schemes in Saudi Arabia.

METHODOLOGY DESCRIPTION OF DECISION SUPPORT SYSTEM FOR EFFICIENT GROUNDWATER MANAGEMENT (DSSGM)

The DSSGM consists of two main models namely: groundwater simulation model and dynamic irrigation water management model. Figure 1 shows the relationship between the irrigation operation and the two models of the DSSGM. The water operator defines the cropping scenarios in terms of crop types and field areas and distribution of crops in the projects. The CDIMS is used to calculate the irrigation requirement and pumping schedule for each field and each crop according to the suggested cropping pattern by the water operator. . The daily, monthly and seasonal irrigation water demands are transferred as water stress inputs to groundwater simulation model. The resulted simulated drawdown and water quality at each level on short and ling term are calculated.

If the resulted change in the water levels and quality are acceptable, the water operation can be implemented according the irrigation schedule from CDIMS. If the resulted changes in water levels and quality with the selected cropping pattern are not acceptable, then the water operator will change the pattern and calculates again the irrigation requirement and schedule. These values are translated and forwarded to simulation model to calculate the impacts on groundwater, and the same step will be repeated again. A functional flow chart of the DSSGM representing these steps is shown in Figure 2.

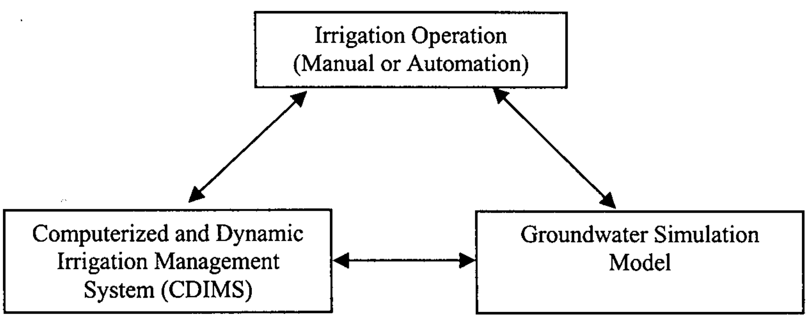

Figure 1. The Relationship between irrigation operator and the DSSGM.

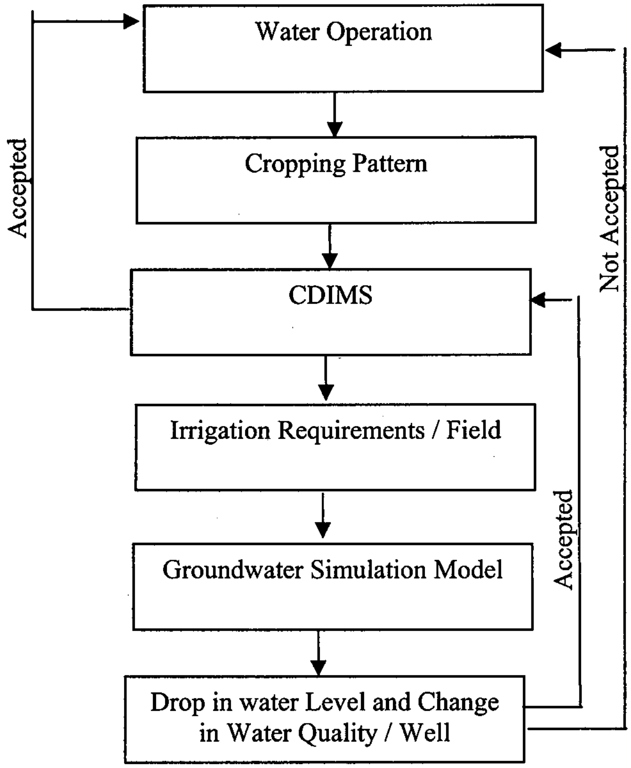

Figure 2. The functional flow chart of the DSSGM.

Groundwater Flow Simulation Model

The groundwater flow simulation model represents the actual groundwater conditions in the aquifer system in the project. It interacts with the CDMIS to assess the long-term decline in water levels and change in quality. Then necessary modifications on cropping pattern can be carried out to protect the aquifer productivity and groundwater quality.

The groundwater flow simulation model is developed and calibrated for the aquifer system to be used predictions of the impacts of different cropping scenarios as selected by the water operator. Visual MODFLOW version 2.8.2 was used to simulate the groundwater flow. The basic information required by different packages of the Visual MODFLOW is:

Aquifer features. This includes the characteristic of the aquifer such as hydraulic conductivity, stativity, aquifer thickness etc.
Well information. This includes information about well such as pumping test, quality, etc
Recharge. This includes the recharge to the aquifer system.
Well pumping. This includes the extraction rate from each well. The data will be transferred automatically from the CDIMS model to Visual MODFLOW format.

The calibrated model is used to predict the effect of selected cropping pattern on the water level and quality changes. Figure 3 shows the activities of model development.

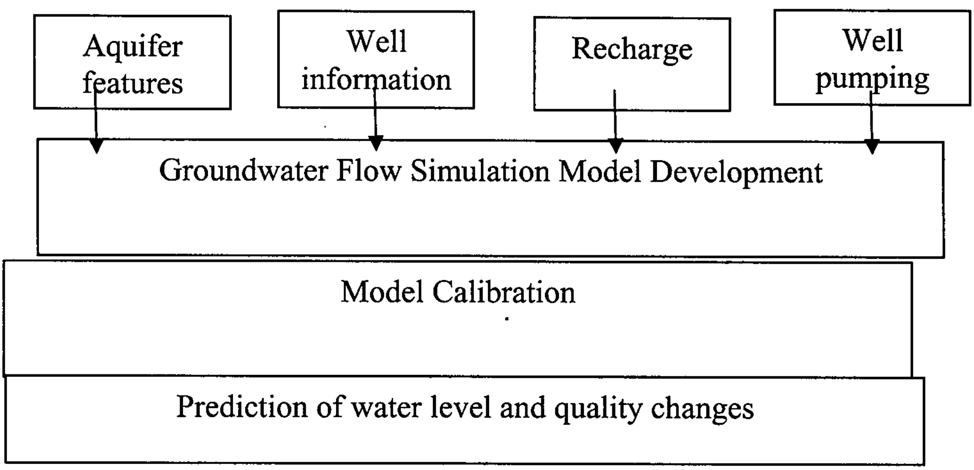

Figure 3. Activities of groundwater flow simulation model development

Computerized and Dynamic Irrigation Management System (CDIMS)

The irrigation water management system depends mainly on identifying the crop-water requirements, crop-irrigation requirements, and crop-irrigation schedule. The procedures reported by Doorenbos and Pruitt [1984] were adopted to calculate the crop-water requirements, crop-irrigation requirements, and the irrigation schedule for the development of the computerized irrigation-water management system.

Calculation of Crop-Water Requirements (Et_{crop})

Calculation of ET_{crop} requires a three-step procedure that determines the following:

1. Effect of climate on crop-water requirements.

2. Effect of crop characteristics on crop-water requirements.

3. Effect of local conditions and agricultural practices on crop-water requirements.

Effect of Climate on Crop-Water Requirements:

Reference crop evapotranspiration (ETo) describes the effect of climate on crop-water requirements. The average daily values of reference-crop evapotranspiration (ETo) during each month of the year are important parameters in the calculation of crop-water requirements (ET_{crop}) during different growth stages. Four methods, Blaney-Criddle, radiation, Penman, and pan evaporation, are modified by Doorenbos and Pruitt [1984] to calculate ETo using the mean daily climatic data for either 10- or 30-day periods. The Penman-Monteith method was introduced by ASCE in 1990 and 1996 to predict ETo (ASCE, 1990 and Allen et al 1996). This method was tested and found to be the best for calculating ETo under the prevailing conditions of Al-Hassa and Al-Fadhly when compared with the measured ETo value among all the above methods (KFUPM/RI, 1991). Consequently, the Penman-Monteith method was selected for the calculation of the ETo for CDIWMS.

The Penman-Monteith method combines thermodynamics, aerodynamics aspects, including resistance to sensible heat and vapor transfer and the surface resistance to vapor transfer.

$$\lambda E_t = \frac{\Delta}{\Delta+\gamma^*}(R_n - G) + \frac{\gamma}{\Delta+\gamma^*} k_1 \frac{0.622\lambda\rho}{P}\frac{1}{r_a}(e_z^o - e_z) \quad (1)$$

where

$$r_a = \frac{\ln\left[(z_w - d)/z_{om}\right]\ln\left[(z_p - d)/z_{ov}\right]}{(0.41)^2 u_z} \quad (3)$$

and

$$\gamma^* = \gamma(1 + r_c / r_a)$$

where

E_t is evapotranspiration rate
P is the atmospheric pressure
R_n is the net radiation
d is the zero plane displacement of wind profile
e_z^0 the saturation vapor pressure of air at height z
e_z is the water vapor pressure in air

G is the heat flux density to the ground
Δ is the slope of the saturation vapor pressure temperature curve
γ is the psychometric constant
γ^* is the psychometric constant modified by the ratio of canopy resistance to atmospheric resistance
λ is the latent heat of vaporization
ρ is the air density
z_w is the height of the wind speed measurement
z_p is the height of the humidity and temperature measurements
u_z is the wind speed at height z_w
K_1 is a dimension coefficient needed to assure that both terms have the same units
r_a is the aerodynamic resistance to sensible heat and vapor transfer
r_c is the surface resistance to vapor transfer
r_{ov} is the roughness length, heat and water vapor
r_{om} is the roughness length, momentum

Effect of Crop Characteristics on Crop-Water Requirements:

The crop coefficient (K_c) values reflect the effect of the crop characteristics on the crop-water requirements (ET_{crop}). The value of ET_{crop} can be predicted by the following relationship:

$$ET_{crop} = (K_c)(ETo) \quad (4)$$

where

K_c = crop coefficient
ETo = reference-crop evapotranspiration (mm/day)
ET_{crop} = crop evapotranspiration (mm/day)

Selection of K_c depends on the crop characteristics, time of sowing and planting, the crop's development stage, and climatic conditions.

Determination of The Crop-Irrigation Requirement

The crop-irrigation requirement (IR) is equal to the quantity of irrigation water required to meet the crop-water requirements (ET_{crop}) after considering all contributions from rainfall (P_e), groundwater (G_e), stored-soil water at the beginning of each period (W_b), salt-leaching requirements (LR), and compensation for water losses during conveyance and irrigation efficiency (E). The crop-irrigation requirement can be calculated from the following relationship:

$$IR = (ET_{crop} - (P_e + G_e + W_b))/(1 - LR/E) \quad (5)$$

where:

P_e = contribution from rainfall (mm/day)
G_e = contribution from groundwater (mm/day)
W_b = contribution from carry-over of soil water (mm/day)
LR = leaching requirements (ratio)
E = irrigation efficiency (percentage)

The leaching requirement can be calculated from the following relationship:

$$LR = EC_w/(2.\text{Max } EC_e) \quad (6)$$

(For drip and high frequency sprinkiers)

where

EC_w = electrical conductivity of the irrigation water, mmhos/cm.

EC_e = electrical conductivity of the soil saturation extract for a given crop appropriate to the tolerable degree of yield reduction.

Max EC_e = maximum tolerable electrical conductivity of the soil saturation extract for a given crop.

During irrigation application, water losses are incurred in many forms: system conveyance losses, uneven distribution of water, water runoff in the field, deep percolation of irrigation water in the soil profile far below the root zone, and evaporation during sprinkling. An efficiency factor should be considered when calculating the crop-irrigation requirements of a certain cultivated area to compensate for the water losses. From local experience about the efficiency of different types of irrigation systems in different regions of the Kingdom, the adopted values for the average irrigation efficiency of the center pivot sprinkler irrigation system is 70%, and for the drip system it is 90%.

Calculation of Irrigation Schedule

The irrigation schedule for a certain crop defines the depth of irrigation application in mm and the interval between irrigation applications in days or hours during the entire growth stages.

The depth of irrigation application in mm can be calculated from the following relationship:

$$d = (PS_a)\, D/E_a \qquad (7)$$

where

d = irrigation application depth in mm

p = fraction of available soil water

D = rooting depth of the crop in cm

S_a = readily available soil water in mm/10 cm

E_a = application efficiency (percentage)

The irrigation application interval (i) for a certain crop, in days, can be calculated from the following relationship:

$$i = (PS_a)\, D/ET_{crop} \qquad (8)$$

In general, plants extract about 40, 30, 20 and 10 percent of the total consumed water from the first, second, third, and fourth quarter of the root depth, respectively [Hansen et al., 1979]. The irrigation interval is calculated according to the consumed water in each soil layer by the roots. The shortest irrigation interval value for any layer of the soil profile is adopted as the irrigation interval for the crop.

Calculation of Water Demands

The irrigation-water demands from the water source (V) by each type of crop at the center pivot can be calculated from the following relationship:

$$V = 10\, A\, IR \qquad (9)$$

where

V = irrigation-water demand in m^3/day

A = area under a given crop in ha

IR = irrigation requirement in mm/day/ha, and

10 = conversion factor to m^3/day.

The irrigation-water demands were calculated within the program for each type of crop at each center pivot on a daily basis. These values are used to calculate the operation time for each center pivot.

Description of CDIWMS

The CDIWMS is user-friendly Windows based software that consists of two separate but linked programs namely: Crop Database Management program and the Irrigation Scheduling Program.

These programs can be run on Microsoft® Windows 95, Windows 98, and Windows 2000 on a Pentium 200 MMX or higher rated PC. The database and the scheduling interface programs were written in Microsoft® Visual Basic and the irrigation program (the computational module) was written in FORTRAN 90. The irrigation program is linked with the interface programs by a Windows dynamic link library (DLL).

Crop Database Management system:

A comprehensive database management system is used to support the CDIWMS with all types of required information pertaining to irrigation fields, crops, water, climate, soil and plants. Presently the system supports 34 different types of crops and 15 different type of soils that are common in Saudi Arabia. Examples of crop types included in the database table are durum wheat, soft wheat, rogo wheat, barley, alfalfa, rodus, and tomato. Users can add, delete, modify, sort, filter and find various field information such as field identification number, crop type, area, soil type, and sowing date as shown in Figure 1.

Every field in the database has a file called crop data file that is used by the irrigation program for irrigation dose computation. The irrigation doses for the whole growth stages of each crop starting from sowing to harvesting dates are saved in special files called life cycle files. The growth period of each crop is divided into growth stages, and each stage is given a certain number of days having a certain number of rooting depths. The crop data editor is used to edit different parameters in the crop data file. The Crop data editor also plots graphs of rooting depths and Kc values with time. This graph is dynamically updated as the rooting depths and lengths of each growth period are modified according to field observation using the crop data editor.

Irrigation Scheduling Program:

The main purpose of the scheduling program is to compute the daily irrigation water requirement for all fields under irrigation simultaneously. The system has several other important functions that include:

- Introduction of new fields to irrigation operation.
- Removal of existing fields from irrigation operation.
- Creating and updating life cycle irrigation files.
- Displaying and printing life cycle files.
- Delaying the irrigation schedule for one day and saving the cause of delaying.
- Suspending irrigation of selected fields saving the cause of suspension.
- Setting selected alfalfa or rodus fields for cutting and saving cutting period records.

Life cycle files are automatically created whenever a new field is added to irrigation.operation. They are also automatically updated every ten days. Updating the life cycle files can also be done by the water operator under special conditions, such as a rain event. The user interface showing all the fields in the database is depicted in Figure 2. The bottom of the screen shows the total number of fields in the database, the number of fields under irrigation, the number of fields that need water delivery and the number of delayed and suspended fields in a particular day

In automatic mode, the undelivered amount in any day is automatically added to next day's schedule as shown in Figure 3. The undelivered dose of the previous day is shown in parenthesis. The rainfall is automatically extracted from the real-time weather data file. Daily doses are automatically corrected for the effective value of rainfall.

SYSTEM APPLICATION

The developed system has been implemented to manage groundwater resources in large irrigation schemes in the Kingdom. The system was calibrated, tested and implemented successfully in several large irrigation schemes containing thousands of hectares of irrigated lands in the Kingdom. These schemes include tens or hundreds of cultivated fields with different types of crops irrigated by different irrigation methods including surface irrigation, drip system, and center pivot sprinkler irrigation system.
The implementation of DSSGM in large irrigation schemes has resulted in saving of about 15 - 25 % of irrigation water. It has also resulted in saving about 20% of the irrigation operation cost, in addition to increase of crop production by 10 - 20%.

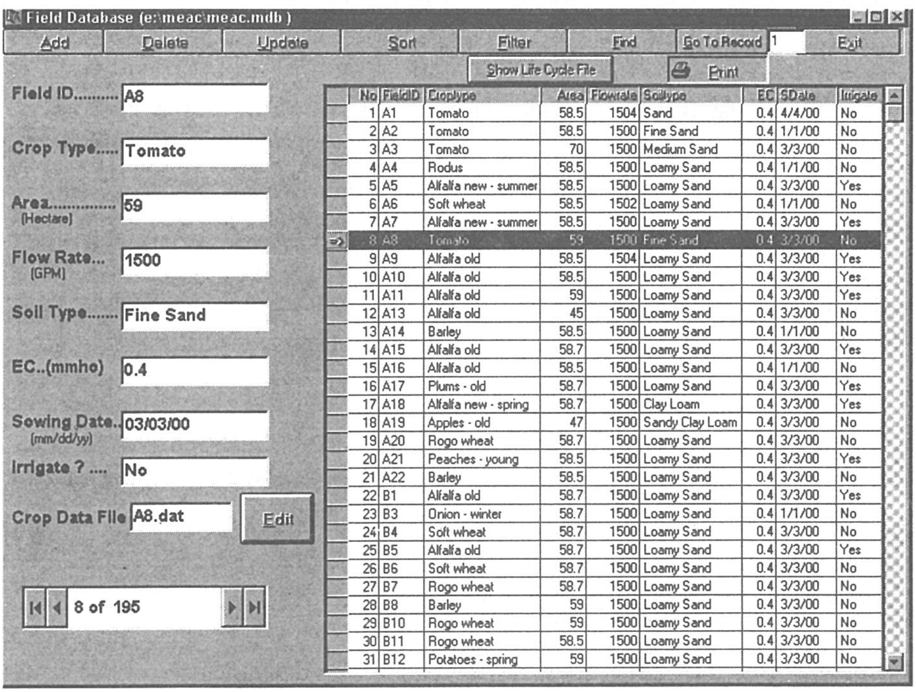

Figure 1. A screen shows the main features of the crop database system.

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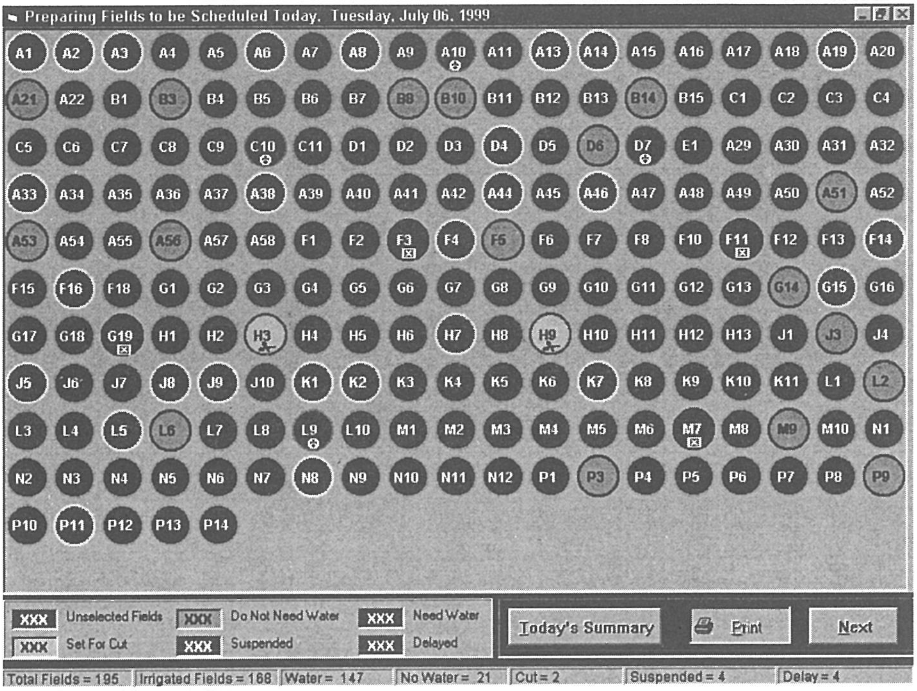

Figure 2. **A screen showing irrigation scheduling status.**

CONCLUSION

The development and implementation of original DSSGM has significant benefits on the operation, control and management of irrigation water in large and multi-field irrigation schemes in Saudi Arabia. The adoption of DSSGM in large irrigation schemes resulted in saving of about 15 - 25% of irrigation water, in addition to reduction of operation costs and increase in crop yield.

Large scale implementation of DSSGM in the Kingdom will help in improvement of groundwater management and conservation, and protection of groundwater productivity for long term use. The use of DSSGM will also help in minimizing irrigation operation costs and maximizing agricultural production. Such irrigation model will be very beneficial to improve irrigation water management and conservation in other countries in arid zones.

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Water Demand Management: Concept, application and Innovations in the Middle East and North Africa

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Water Demand Management: Concept, applications and innovations in the Middle East and North Africa

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SUMMARY

The paper examines the water shortages in the Middle East and North Africa and distinguishes between the structural causes (nature and population growth) of water shortages and the non-structural causes (unwise and inefficient use, pollution, and over exploitation) brought about by the way water is managed. The paper argues that the supply driven approach, searching for new supplies to match the perceived demands, further worsened the natural water shortages and will not enhance water security in the water scarce region. Accessible freshwater sources are tapped beyond their capacity. Securing additional water from across national borders, while achievable, remains costly and risky. Desalinated water is a potential source but remains costly and out of the reach of most MENA countries until desalination costs are reduced.

There is no other region on earth where the need is so acute for a major shift in water policies from the supply approach to the demand management approach within integrated water resources management, in which the search for additional water sources does not begin until the perceived demands on water are challenged and all possibilities are exhausted for manipulating them in order to match the existing supplies. The demand can be manipulated through:

- efficient allocation in quantity and quality to the competing users of water (agriculture, industry, and domestic) to ensure that water is used wisely and optimally for the public interest;
- efficient water use by all users to eliminate wasteful consumption and reduce consumptive use of water;
- and sufficient and efficient environmental protection for pollution control and maximized safe recycling.

The paper draws on the experience of several countries in MENA and suggests that only comprehensive, sustained, and proactive interventions can achieve lasting results. Sporadic, ad-hoc and poorly targeted water conservation and education drives alone rarely achieve results. The shift to water demand management starts with an understanding of the non-structural causes of water shortages and recognition at the highest policy level for the need for such a shift. Institutional and sector reforms that are supportive to the water demand management shift are necessary. Rational planning processes are needed to ensure that water is developed, allocated, used, and protected in ways that ensure efficient, sustainable and beneficial use of water in the public interest.

The paper reviews existing management tools, enabling strategies, technologies and innovations that are tested and available. Additional innovations are proposed. Decentralized but holistic wastewater management is proposed to facilitate the recovery of every drop of wastewater and site-tailored modular wastewater systems suggested. The closed-water-loop-system is presented as a working model in order to translate the decentralized wastewater management concept and the demand management principles into practice at the household and the community levels.

KEYWORDS: water resources, water demand management, pollution control, water allocation, wastewater management, recycling, Middle East and North Africa.

INTRODUCTION: TRENDS IN WATER MANAGEMENT:

Management of the water sector generally comprises four groups of functions (Figure 1):

1. Assessment and development of water resources (groundwater, surface water, non-conventional water sources) to augment and enhance availability of water.
2. Allocation of available water resources to the competing groups of water users (municipal, commercial, industrial, agricultural).
3. Utilization of water by the various water users (delivery, consumptive use, and waste generation).
4. Environmental protection and pollution control for safe integration of waste in the water cycle and recycling.

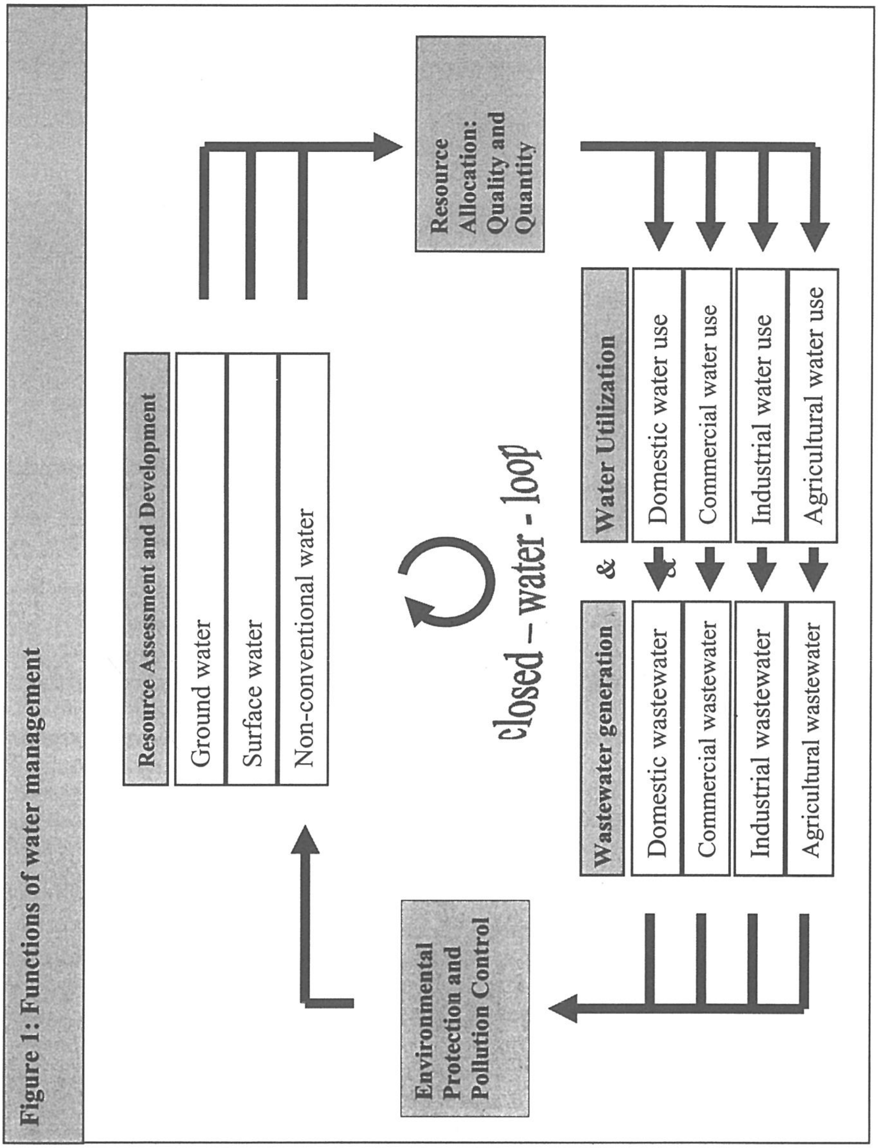


Figure 1: Functions of water management

Employing a combination of these groups of functions, water managers try tirelessly to strike a balance between the available water resources and the demands on water by either:

- Supplying more water (supply management or augmentation) to match the perceived rising demands focusing mainly on the assessment and development of new water source and supply facilities

  or
- Manipulating the demand on water (demand management) to match them with available supplies focusing mainly on the other three groups of functions namely: efficient allocation; efficient water utilization; and effective pollution control and recovery of wastewaters.

Historically, water resources policies and management practices have been supply driven. To meet the perceived rising demand, intensive efforts were invested in the assessment and development of new water sources and installation of delivery systems with little or no attention to the other three groups of functions. The main outcomes of the supply approach are the utilization of freshwater sources beyond their renewable capacity leading to their depletion. Nearby and better quality sources are first used. Distant sources are sought at higher cost. Nonrenewable groundwater is mined, and lesser quality water is used. When we run dry, we turn to the sea.

As the demand on water goes unchallenged so does the production of waste. Water management practices historically paid little or no attention to safe management of the huge volumes of wastewater produced. The collection and disposal mind-set prevailed because of concerns over public health protection. Cesspits were built to make wastewater disappear in the ground. Water intensive and centralized sewer systems were built to remove wastewater from the immediate environment of the communities using water as a transportation medium. When rivers, lakes, and accessible groundwater became polluted, wastewater treatment plants were built. Yet, a significant proportion of the scarce water sources continue to be consumed by pollution and the much needed water conservation drives can not be accommodated because of the intense water requirements for flushing the sewers.

Recent trends in water resources management indicate that water is increasingly recognized as: a valuable resource for the health and well-being of the society and its sustainable development; a finite resource which must be used efficiently and wisely; a renewable resource which must be kept clean and its quality protected; and a shared resource which must meet the needs of competing current users (humans and non-humans) and future generations.

There is increasing recognition that no supply strategies can keep pace with the present rate of population growth and demand even in the water-rich and economically-enabled countries. Water management practices now explore demand management solutions to ensure optimal, efficient, sustainable, and beneficial use of water. Allocation between the competing water users is used to ensure that the water use pattern supports the public interest with emphasis on meeting the basic human needs for domestic water supplies. Water efficiency solutions are adopted to minimize the wasteful consumption and reduce the consumptive use of water. Environmental protection and pollution control policies are considered within the framework of integrated water resources management. Wastewater is being considered within the total water cycles and pollution control policies not only aim at stopping the pollution of the scarce water sources but also maximizing recycling and reuse of wastewater within the water budget of the households, communities, industries, commercial establishment and agriculture. Decentralized wastewater management is being explored for greater protection and many more opportunities for reducing the nonproductive consumption of water in waste transportation and maximizing the recycling opportunities (Bakir, 2001a&b)

MENA WATER SHORTAGES

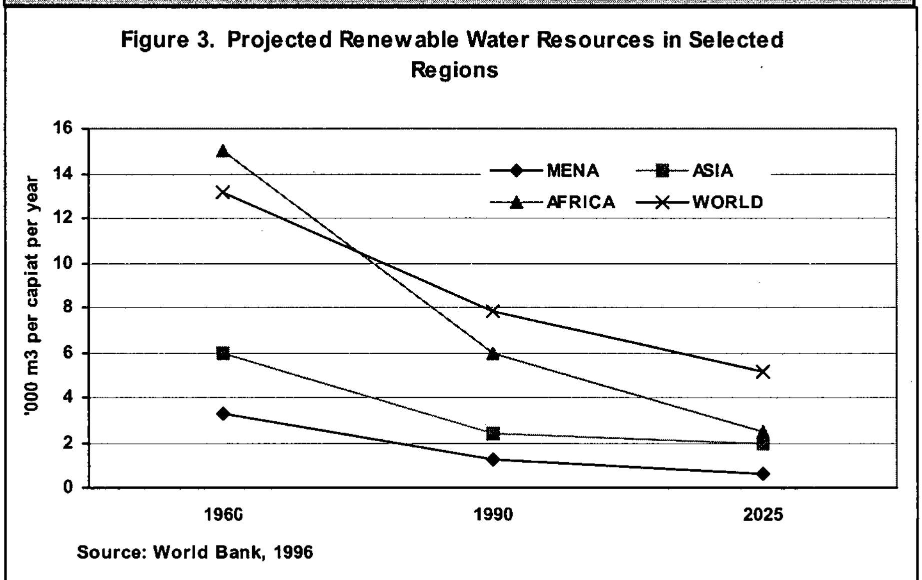
Water Scarcity and its Impact

MENA is the driest region in the world with less than 1% of the world's freshwater resources (Table 1). Freshwater availability has declined rapidly to a crisis level. MENA has the lowest per capita water availability and the regional average annual per capita renewable water dropped from 3300 cubic meter in 1960 to about 1250 cubic meter in 1995 and is expected to drop to 650 cubic meter in 2025 (Figure 2). The water scarcity crisis in more acute Jordan and Yemen with water availability figures in 2000 (Table 2) much lower than the projected regional average for 2025.

Table 1: Distribution of Net Renewable Water Resources by Region (Total and Per Capita), 1995 estimates		
	Total Availability (billion m^3/year)	Per Capita Availability (m^3/year)
Oceania	769	36619
Latin America	10766	23103
North America	5379	18742
Eastern Europe and Central Asia	7256	14659
Africa	4184	7485
Western Europe	1985	5183
Asia	9985	3283
MENA	355	1250

Source: World Bank (1996)

Figure 2: Projected Renewable Water Resources in Selected Regions



Water scarcity is regarded as one of the main constraints to social and economic development and even a source of insecurity. Municipal water supplies are becoming increasingly insecure and their quality is degrading. Some cities, such as Amman and Damascus, are running thirsty. Water supplies are interrupted routinely and rotated due to severe water shortages especially in the summer. Intermittent water supplies, accompanied by severe water quality deterioration, are common and so are outbreaks of water borne diseases.

Water scarcity is the most significant constraint to the extension of safe water supply services to needy communities. In Oman and the West Bank, for example, providing a water supply system to a community is a question of finding the water source, not the funding for the system construction. Many new and existing water supply schemes in Palestinian communities remain without running water for extended periods of time.

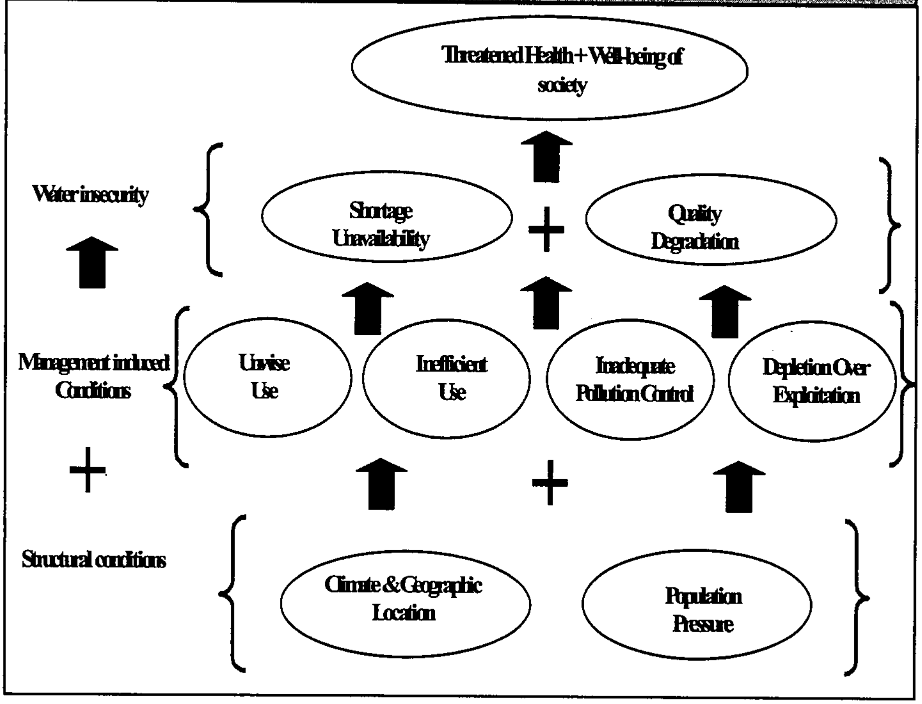
In the absence of irrigation water, farmers turn to untreated or partially treated wastewater for food production with significant public health implications.

Causes of MENA Water Shortages

Understanding the causes of the water shortages in MENA is a prerequisite for developing effective water management strategies to avert further decline in the water availability. The water shortages in the region are a result of structural and non-structural conditions (Figure 3):

1. Structural conditions related to geographic location, climatic characteristics and the population growth. Water policies and management practices can impart little influence on these conditions, at the least in the immediate and near future.
2. Non-structural conditions or management-induced conditions brought about by existing water policies and management practices. These conditions can be changed and their impact reduced through improved water management policies and practices.

Figure 3: Causes and impact of water shortages in MENA



Source: Bakir

Structural conditions causing water shortages
Water scarcity in MENA is largely due to natural causes. The region's climate is arid and semi-arid characterized by low and erratic rainfall. Eight of MENA countries receive less than 100 mm per year and only 4 countries receive more than 300 mm per year (FAO, 1997). Most of the region's river flows originate from outside the region.

The rapid decline in the per capita availability is a result of the rapid population growth, urbanization and socioeconomic development. The population doubled in the past 30 years and is predicted to double in the next 30 years. Urban areas are home to about 60% of the region's population and cities are growing at an annual rate of 4 percent (World Bank 1996).

Management induced conditions causing water shortage

Unwise, inefficient and often wasteful use of water by all user sectors
The water shortages are aggravated by the way water is utilized. Water is often used wastefully, unwisely and inefficiently by the agriculture, municipal, industrial and commercial users. Irrigated agriculture is the biggest water user in the region with share ranging from less than 70% in Algeria, Bahrain, Cyprus, Kuwait and Lebanon to over 90% in Iran, Iraq, Morocco, Oman, Saudi Arabia, Sudan, and Syria (Table 2). Meanwhile, municipal and

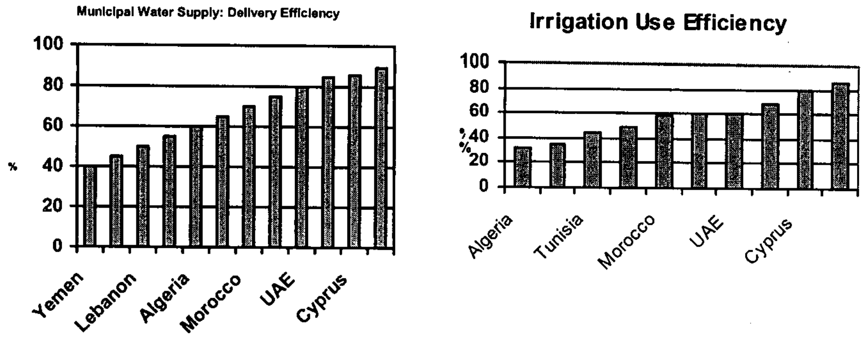
industrial demands are on the rise and there is not enough water available to them. Cities are running dry and their water supplies are increasingly becoming insecure.

Table2. Annaul Internal Renewable Freshwater Resources and Wthdrawals							
Country	Annual availability (m3 per capita)	Annual Withdrawals			Sectoral Withdrawals		
		Year	% of available resources	Per Capita (m3)	Domestic	Industrial	Agriculture
Algeria	442	1990	32	180	25	15	60
Bahrain *	7	1991	5980	465	39	4	56
Cyprus*	1213	1993	23	331	24	2	74
Egypt	26	1993	3,061	920	6	8	86
Iran	1,898	1993	55	1,165	6	2	92
Iraq	1,523	1990	122	2,368	3	5	92
Jordan	102	1993	145	187	22	3	75
Kuwait	...	1994	...	307	37	2	60
Lebanon	1,463	1994	27	444	28	4	68
Libya	143	1995	486	783	9	4	87
Morocco	1,058	1992	37	446	5	3	92
Oman	388	1991	124	658	5	2	94
Palestine	...	...	...	...	...	...	...
Qatar *	93	1994	559	528	23	3	74
Saudi Arabia	111	1992	708	1,002	9	1	90
Sudan	1,187	1995	51	669	5	1	94
Syria	434	1993	206	1,069	4	2	94
Tunisia	367	1996	76	295	14	3	83
UAE	61	1995	1,405	954	24	10	67
Yemen	226	1990	72	253	7	1	92

Source: World Resources Institute (2000) & FAO (1997)*

Water is inefficiently used. Water utilization by all water user groups is characterized by great inefficiencies. in the water delivery systems and during utilization. Losses from municipal water delivery and supply systems reach as high as 60% (Figure 4) exceeding the quantity of water reaching the consumers. In agriculture, as much as 50% of the produced water is lost during production, storage, and conveyance. Once water reaches it intended target, it is used inefficiently as consumers have no incentive to conserve. Domestic and agricultural supplies are subsidized and the cost to the consumer is far below the real cost of water. Low pricing encourages wasteful consumption of water and offers no incentives to conserve and invest in water efficiency solutions. Inefficient and water wasting fixtures are widely used and public building are water wasters. Best quality water is used in ornamental gardening. In agriculture, water is often used on land and crops with low productivity and low added value on using water. Irrigation methods are inefficient. Flood irrigation efficiency is barely 30%. Water is used for producing export crops even in those countries with the lowest water availability. Exporting crops is effectively exporting the water needed to produce them.

Figure 4: Water use efficiency can be enhanced.



Source: Macoun, 2000

Excessive abstraction and depletion of water resources

The supply-driven water resources policies exacerbated the water shortages in the region. Paying minimal attention to water use inefficiency, countries intensify their search for new water sources to meet the rising demand on water. Groundwater and surface water resources in some of these countries are shrinking to crisis situation and their quality is degrading. Eight MENA countries have tapped their existing resources beyond their renewable availability (Table 2). Jordan, entirely dependant on its internal water resources, withdraws 45 percent more from its internal renewable resources than is being replenished and is currently developing its nonrenewable groundwater sources. Gaza aquifers are mined rapidly with the water tables dropping at the rate of 10-20 cm per year (UNEP 1999). In Sana'a the water table also dropped seriously as a result of over exploitation (Environmental Protection Council, 1995). Seawater intrusion in the Batinah coast of Oman caused non-reversible damage to the coastal aquifers and complete loss of land (UNEP/UNESCWA 1992). Some countries are mining their non-renewable fossil groundwater. Saudi Arabia, UAE, and Libya are the largest users of fossil water (FAO, 1997). Fossil groundwater in Libya accounts for 95% of the country's freshwater withdrawals (UNEP, 1999).

Insufficient and inefficient pollution control

Pollution continues to be a serious threat to public health and a significant freshwater consumer. Water management practices in MENA continue to pay little attention to safe management of the huge volumes of wastewater generated. The main sources of pollution are:

1. Unsafe management of domestic wastewater (disposal of untreated or poorly treated wastewater and seepage from poorly constructed and maintained onsite sanitation systems). Existing urban wastewater systems are insufficient and inefficient and in many cases they aggravated the problems they were built to solve.

2. Uncontrolled disposal of industrial waste into sewers, land and water bodies
3. Leaching from unsanitary solid waste landfills
4. Seepage from agrochemicals (excessive use of fertilizers and pesticides)

UNEP Global Outlook 2000 (1999) reports that the Sebou river in Morocco, Sidi Salem reservoir in Tunisia, the Nile, and Al-Assi and Barada rivers in Syria are severely polluted from uncontrolled industrial, domestic and agricultural discharges. It further reports that the Mitidja and Saida aquifers in Algeria, the shallow aquifers in Sana'a, Batinah cost in Oman, and Cyprus are contaminated Nitrate levels in Gaza reached 40 ppm, 4 times higher than WHO guidelines (World Bank 1996).

CURRENT COPING STRATEGIES

To cope with water scarcity, several MENA countries supplement their fresh water with treated wastewater and desalinated water (Table 3). Wastewater is widely recognized as a potential and reliable water source of growing availability. Jordan's and Tunisia's water policies count recycled wastewater in the national budget (Jordan Ministry of Water and Irrigation, 1998 & Bahri, 2001). In Syria, Lebanon, Jordan, Iraq, and West Bank and Gaza, 200 million cubic meters of wastewater are used annually for irrigation (UNEP1999). Partially treated and even untreated wastewater is used in agriculture in Yemen and Syria raising serious public health concerns. In GCC countries, about 400 million cubic meter of the annual 918 million cubic meter of treated wastewater are tertiary treated and reused for irrigating non-edible and fodder crops and urban landscaping. About 60% of the partially treated sewage is discharged to the sea (UNEP 1999).

Supported by their substantial energy and financial resources, the extremely water short

Table3: Use of NonConventional Water in MENA Countries

Country	Reused treated wastewater			Desalination Water			Recycled & Desalinated
	Million m³/yr	% of agriculture withdrawals	% of total withdrawals	Million m³/yr	% of domestic and industrial withdrawa	% of total withdrawals	% of total withdrawals
Kuwait	52	16	9.7	231	107.9	42.937	52.602
Qatar	25.2	12	8.8	98.6	132.7	34.609	43.454
UAE	108	7.7	5.1	385	55	18.264	23.387
Bahrain	8.03	5.9	3.4	44.1	42.3	18.436	21.793
Saudi Arabia	217	1.4	1.3	714	41.8	4.196	5.471
Jordan	50.3	6.8	5.1	2	0.8	0.203	5.315
Cyprus	11	7.1	5.2	...	...	...	5.213
Oman	26	2.3	2.1	34	45.3	2.780	4.906
Libya	100	2.5	2.2	70	11.7	1.522	3.696
Syria	370	2.7	2.6	...	...	...	2.568
Algeria	...	...	...	64	3.6	1.422	1.422
Tunisia	20	0.7	0.7	8.3	2.4	0.270	0.92
Egypt	200	0.4	0.4	25	0.3	0.045	0.408

Source: FAO, 1997

countries of the GCC turned to desalination of seawater to meet the increasing demand on water. The power intensive and extremely costly desalination technologies remain beyond the reach of the majority of the region's countries. The cost of desalinated water is still high compared to the tariff charged.

Other water scarce countries, such as Jordan, explored cross-border water transfers especially from Turkey but the transfers never materialized for political reasons and concerns over security of the new supplies. Small scale water transfers from Syria to Jordan help alleviate the summer water shortages. Huge water bags from Turkey are transported to Northern Cyprus. Other transfer schemes from Iran to the Gulf countries are also being explored.

FUTURE CHOICES: THE DEMAND MANAGEMENT APPROACH

The structural and non-structural causes of water shortages in MENA must be addressed in order to enhance and safeguard the water supplies for sustainable development. Water supplies have to be augmented to overcome the natural shortages and to enhance water availability.

The demands on water have to be challenged and manipulated. Issues of population growth and urbanization trends have to be addressed by the society but they remain beyond the reach of water managers who can impart little influence on them, at least in the short or medium term. Water management practices must be improved to overcome the non-structural causes of water shortages.

The supply driven approach worsened the natural water shortages crisis and the opportunities for further augmentation of water supplies are limited. Many countries have tapped all their accessible and known resources beyond their virtual capacity. Securing additional water sources from across national borders, while achievable, remains costly and carries a great deal of security risks. Desalinating seawater for additional water supplies is achievable, but remains costly and within the near future, it will not be affordable to most MENA countries unless significant cost reductions are achieved.

Before embarking on development of costly additional water sources, a new approach to water resources management in the region is needed. The demand management approach, successfully tried in may countries worldwide and in MENA such as in Bahrain and Tunisia, focuses on manipulating the demands on water in a serious attempt to match them with the available water resources. Each nation's water resources must be protected, conserved, developed, managed, used, and controlled in ways which ensure efficient, sustainable and beneficial use of water in the public interest. In the water stressed countries of MENA, every drop of water including wastewater, must count. The water resources and wastewater management policies must come together in addressing the water cycle in a holistic manner within the umbrella of integrated water resources management processes. Water must be used efficiently to reduce the consumptive use of water and wastewater flows. Wastewater flows must be managed effectively to safeguard public health, and protect the freshwaters from pollution. They must be reintegrated safely in the water cycle and accounted for in the water budget of the household, community, industry, and agriculture.

Many common misconceptions surround the water demand management approach within the professional community. Water demand management is often perceived as crisis driven water conservation drives. Water utility managers often perceive the water demand management measures as sporadic and low profile public awareness exercises managed by marginalized and poorly staffed water conservation or water education units.

The demand management approach stipulates that new water sources and additional supply facilities will not be developed until after exhausting all available opportunities for reducing the demand on water to match the existing supplies. The Demand management approach addresses the non-structural causes of water shortages and places the following three groups of functions at the heart of integrated water management policies and establishes them as main stream operational strategies:

1. Efficient allocation of water amongst the competing groups of users to ensure that water supplies are used wisely and optimally in the public interest
2. Increasing the efficiency of water use to eliminate wasteful consumption and reduce consumptive use of water while maintaining its social benefits
3. Strengthening environmental protection policies and pollution control to safeguard the quality of the scarce freshwater and safely reintegrate wastewater into the water cycle as a component of the water budget of households, communities, industries, and agriculture.

Water Allocation for Serving the Public Interest

Water allocation amongst the competing water user groups is the main tool available for ensuring that water is used wisely and optimally in a socially beneficial manner in the public interest. The severe competition between the various water user groups (domestic, commercial, industrial, and agricultural) will only get worse. As the population continues to grow, the municipal and domestic demand on water will continue to rise. Industrial and commercial water demands will also grow due to the changing nature of the region economies from large dependence on agriculture to increasing dependence on the industry, tourism and services.

Public health protection is the most socially beneficial use of water. To protect the public health and meet the basic human water needs, the domestic and municipal water demand must be met first and the highest quality water must always be reserved for the domestic municipal water requirements. In times of water crises such as droughts, the domestic water demand is met first at the cost of the other competing demands.

Agriculture is the largest water user with the least water productivity (value added by using water), the contribution to GDP is lowest, and the employment generated from using water is lowest (World Bank, 1996 & Macoun 2000). Agriculture uses 75% of Jordan water resources and contributes only 3% to its GDP (Government of Jordan 2001). Agriculture appears to be under severe pressure to yield part of its share of the water resources. In the summer of 2001, Jordan cut by 30% the agriculture water supplies to the Jordan Valley (Jordan Times, 2001).

The industrial and commercial water user groups are viable economic entities capable of adding high economic and social returns (employment for example) on utilizing water. If the water is treated as a commodity and is left to the market forces and subsidies on water are removed, the industrial and commercial water users might afford the real cost of water.

The Efficiency Solution

Using water more efficiently in all applications is the way to eliminate wasteful use of water and reduce the consumptive water use without reducing the social benefits of water. Water efficiency solutions by all water using groups (municipal, agriculture and industrial) generally include:

1. Increasing the efficiency of the municipal, agricultural, and industrial water delivery and supply systems
2. Eliminating wasteful consumption of water by all water user groups
3. Increasing the efficiency of water utilization by all water user groups
4. Allocating water to the more efficient and productive applications within each water user group

5. Using marginal and low quality waters (brackish and treated wastewater) and quality allocation to match the water quality with the requirements of the intended water use.

The demand management approach calls for institutionalizing comprehensive, sustained and long-term water efficiency measures within the management practices of the water suppliers. The demand management approach calls on the water suppliers to play a proactive role and invest not only in improving the efficiency of the water supply systems but also in extending their responsibility to include efficient water use by the water consumers.

Efficient municipal water use

Investment in municipal water efficiency not only saves the best quality and scarcest water from wastage but also spares the millions of dollars necessary to produce it. Tunisia and Bahrain offer two examples where significant water savings were realized through the execution of aggressive, comprehensive, and sustained municipal water efficiency programmes combining: increasing supply system efficiency through leakage control and better management; universal metering and pricing; improved customer services; and public education for creating a water conservation culture (Box 1 & Box 2).

Box 1: Municipal and Industrial Water Demand Management in Bahrain

Source: Qamber (2001)

The demand on water in Bahrain increased from 16 mg/d in 1975 to 48 mg/d in 1985. Corrective measures were introduced in 1986 to manage water demand within affordable production and safe limits of extraction. Demand projections in 1990 indicated that demands could not be satisfied with available resources and a new source must be made available. A strategy was devised in order to match the legitimate domestic and industrial demands with the available production and supply facilities. A maximum supply ceiling of 70 mg/d was introduced in May 1994 and a significant investment was made in a comprehensive demand management programe to increase supply system efficiency, minimize wasteful and excessive use, and conserve water, and enhance water quality. Practical measures included: none standard service pipe replacement; waste detection and management; pressure control; metering and tariff introduction; plant protection; water conservation; and enforced water bylaws.

Leakage losses dropped from 25% in 1993 to 19 percent in year 2000 indicating an 81% distribution system efficiency (Chart a). Unaccounted for water (UFW) dropped from 35.5% in in 1993 to

The first priority water efficiency measure is reducing water losses in municipal water supply schemes through efficient management of the production, conveyance, storage, and distribution facilities. System efficiencies can be increased to over 80% as in the case of Bahrain, Cyprus, UAE and recently Tunisia (Figure 4). Improving efficiency of municipal supply systems enhances the public's confidence in their water supply system and encourages positive behavioral change towards conserving water. Bahrain succeeded in significant manipulation of water demand as also demonstrated in Box 1. The Bahrain experience demonstrates that reducing the water losses in municipal systems defers and may eliminate urgent investment in additional water sources and expansion of the water supply system in addition to safeguarding the water quality in the municipal systems (Qambar, 2001). In Tunisia sustained leakage control efforts over a period of 10 years reduced the unaccounted-for-water (UFW) from 24.1% to 14.5% (Box 2).

Box 2: Water Demand Management in Tunisia (Source: Limam, 2001)

Like most EMR countries Tunisia has a very limited water supply and a constantly rising water demand. To cope with water supply shortages crisis, Tunisia embarked on a comprehensive and sustained water demand management programme since 1991. Tunisia water demand management strategy combines: Increasing water supply system efficiency and controlling leakage; Universal water metering and pricing for conservation (rising-block-tariff); Public awareness and education to create a water conservation culture, Although the number of consumers increased 57% between 1990 and 1999, the total water consumption increased by only 39%. Major achievements were realized:

- Unaccounted-for-water decreased from by 24.1% to 14.5%
- Institutional, public buildings and commercial water connections (in m3/year/connection) dropped by 37%
- Tourism per bed consumption (liters/day/bed) dropped by 18%
- Household consumption (m^3/year/connection) dropped 5%.
- All users per connection consumption dropped 11.6%

TUNISIA MUNICIPAL WATER SUPPLY PERFORMANCE INDICATORS: 1990-1999				
Indicators	Unit	1990	1999	Change
1- Number of customers	Thousands	938	1478	+57.5%
2.Water produced	Million m^3	276,8	337	+21.7%
4- Specific consumption * Household	m^3/year/connection	137	130	-0.5%
* Public connections: (including commercial)	m^3/year/connection	1304	784	-39.9%
* Tourism	liter/day/bed	573	472	-17.6%
* All uses	m^3/year/connection	207	183	-11.6%
CONVEYANCE NETWORK				
5- Length of network	Km	5490	6831	+24.4%
6- Unaccounted for water	%	7,5	5,6	-
DISTIRIBUTION NETWORK				
7- Length of network	Km	15550	25346	+62%
8- Unaccounted for water	%	24,1	14,5	-
9- Index of loss	m^3/day/km	10,9	5	-
GLOBAL NETWORK				
11- Length of network	Km	21040	32159	+52%
12- Unaccounted for water	%	29,7	19,3	-

Domestic water metering and pricing are effective tools for reducing wasteful use of water and increasing water use efficiency. Water metering increases people's awareness of their water consumption and encourages consciousness. The rising block tariff structures have been used widely as disincentives for wasteful water use and incentive for efficient water use and have proven their effectiveness as water conservation tools especially when coupled with consumer education exercises. Jordan's aggressive domestic water pricing structure includes charges for both water supply and wastewater management (Table 4) and attempts to provide subsidized rates for the low end consumers and prohibitive structure for the high end consumers. The entire quarterly water consumption is charged at the unit cost of the last cubic meter consumed. For example the quarterly water bill would be JD 11 (US$ 15.53) if a household consumed 69 cubic meters charged at JD 0.155 (US4 0.23). The same household would pay JD 32.733 (US$ 46.23) for 70 cubic meters at the next block rate of JD 0.464 (US$ 0.66).

In the MENA, charging for water is customary and water pricing is generally accepted but the debate continues on how much to charge. Advocates for system sustainability suggest complete cost recovery. In the context of water use efficiency, water rates higher than those necessary for cost recovery might be necessary to discourage wasteful use of water and encourage positive behavioral change and investment in water efficiency solutions. While developing water rates, planners must ensure that water is always available for meeting the basic human needs at a reasonable and affordable cost. Water pricing must permit the supply of sufficient supply of water the basic human needs at an affordable cost to the low-income groups within the society and thus ensure that water efficiency measures never harm public health.

Indoor and outdoor water efficiency brings direct benefits to the consumers whose spending on water can be reduced, especially if aggressive conservation pricing is adopted. Due to water scarcity and the rotational/intermittent nature of many urban supply schemes, consumers obtain limited supplies from public supply systems to last them for as long as a week when the supply is suspended. Consumers often have no choice but to conserve and stretch their share or ration of water to last for longest duration in order to avoid the high cost and inconvenience of buying additional transported supplies. These consumes are looking for water enabling efficiency solution.

Indoor water efficiency can be boosted through the use of improved water saving fixtures and appliances such as low volume flush toilets, dual flush toilets, high performance showerheads, showers and facet aerators, and front-loading washing machines without inconveniencing the water users. New air-displacement flush toilets, using 1.6 litre per flush, are under development (Moore 2000). Water saving technologies are proven and available and must be made widely reachable. Water utilities must encourage wider application of these technologies and invest in retrofitting programmes or provide financial incentives. Legislation, revised building codes, import and manufacturing restrictions, and tax incentives are all necessary measures for ensuring the availability and encouraging wider use of domestic water efficiency solutions.

Private and public landscaping in urban areas are big outdoor water users in the region. Solutions for water efficient landscaping include the use of low quality water and recycled wastewater or greywater in landscaping. Urban landscaping in the GCC countries, such as in Oman and Dubai, is largely dependant on recycled wastewater. Xeriscaping utilizes native and drought tolerant plants and water efficient designs to create beautiful surroundings with as little water as possible.

Technologies are also available for using low quality water for non-potable water applications such as landscaping to free up the most expensive, scarcest best quality water.

Separation and recovery of greywater for landscaping can readily be done with small investment. Brackish or lower quality water aquifers, contaminated from onsite sanitation systems, can be used for landscaping and toilet flushing. The water authorities in Cyprus provide financial incentives and equipment to those households that wish to install graywater systems or drill a borehole for utilizing the low quality shallow aquifers for landscaping and toilet flushing (Kambanellas, 1998 and Iacovides, 2001). Small wastewater recycling systems at the scale of the household, residential building or neighborhood offer a cost effective and robust means of closing the water loop. In Saudi Arabia, a residential development company reports water savings of 40% in residential buildings equipped with small wastewater recycling systems (Badruddin, 2000).

Urban rainwater harvesting for use in toilet flushing and other non-potable applications, during the rainy season, will free large amounts of fresh drinking water which need not be produced and remain in reserve for use in the dry summers. Utilizing rainwater as it comes during the rainy season will eliminate the need of costly large rainwater storage cisterns and make it appealing to the householders. Water utilities may reap many benefits but the urban dwellers will have a fewer returns for their investment in constructing rainwater harvesting system and modifying their plumbing system. Homeowners' water savings occur during the rainy season when urban supplies are more abundant and the lower household consumption is charged at the low tariff block rate. The water utilities can encourage the use of rainwater harvesting by offering direct financial incentives towards the construction of the system or cash grants for the volumes of water saved towards the summer water bills.

The enabling technologies and the water pricing tools must be compounded with behavioral change and a water conscious culture which is influenced partly by people's knowledge of how much water they consume, for what purpose, at what cost and what consequences. The Bahrain customer information services notify the customer of their past consumptions (Qamber 2001).

Public education and awareness is of paramount importance. However there are a lot of misconceptions. Water utilities often target the wrong audience with their across the board public awareness exercises and water education campaigns. Water awareness campaigns will have little credibility with people who barely have enough water for their basic needs while the big consumers continue to wastefully use water. Water efficiency campaigns must be targeted at the right audience and must be closely coordinated with other demand management measures in order to ensure long-term behavioral change.

Water efficiency in agriculture

The agriculture sector is under pressure to yield part of its water supply to other growing domestic and industrial users who can provide higher social and economic returns on using water. The agriculture sector can increase its water use efficiency to deliver competitive social and economic returns by producing more with less water. Losses from the water storage, conveyance and distribution facilities can be reduced by lining water canals, replacing open canals with pipes, lining and covering on farm storage facilities. The irrigation efficiency can be improved significantly by departing from the inefficient flood irrigation methods to drip irrigation. Irrigation management services should be established to guide farmers on when, how, and how much to irrigate. To boost the irrigation efficiency in agriculture, Oman offered incentives and subsidies to encourage farmers to use drip irrigation.

The productivity and efficiency of water use in agriculture can be improved by only allowing irrigation of crops and on lands with optimum crop yield per cubic meter of water. Better pricing of irrigation water can provide rational incentives to reduce wasteful irrigation and shift to more productive agriculture practices.

Countries may have to offer import incentives in order to encourage importation of water intensive crops and to discourage their local production. Bans might have to be placed on certain farm lands known for their low yields for every cubic meter of water. It might be necessary for countries with severe water shortages to stop farming of export crops. Exporting one ton of oranges is effectively exporting the 400 cubic meters of water that is needed to grow it. Likewise, importing one ton of bananas is effectively importing the 900 cubic meters of water necessary to produce it.

Various crops require varying qualities of water and the low quality marginal waters, such as brackish water and recycled wastewater, can be used. Crops which require a very high quality water might have to be replaced with salt tolerant crops to make use of the brackish water. Recycled wastewater is widely used in agriculture. Increasing use of recycled wastewater will become even more necessary in the future as the better quality irrigation water is shifted to municipal and industrial applications.

Water efficiency in the industry

The demand of growing industrial sector will rise. The total amount of water used in the industry is determined by the mix of products produced, the intensity of water requirements in the production process, and the efficiency of the production processes. To produce more with the available quantity of water, it necessary to examine the mix of products and shift to products requiring less water to produce. Water intensive products, such as textile processing, can be avoided. Water intensive processes can be replaced with more efficient and less water dependent processes. Industrial wastewater must be recycled and as much as possible and used, together with treated domestic wastewater and other low quality waters, in appropriate applications within the production processes.

The industrial sector is considered viable economic entity capable of competing for the scarce water supplies in the open market and adding a great value on using water. Industrial water pricing, which reflects the real cost of water, will encourage conservation and investment in water saving solutions.

Environmental Protection, Pollution Control, and Recycling

As we use water in our homes, buildings, industry, and agriculture, we generate wastewater. The generated wastewater will either end up consuming the scarce freshwater resources if poorly managed or can be brought back into the water budget as a non-conventional water source. Pollution control through effective wastewater management is the tool available to water resource managers to protect the scarce water resources and recover water. The efficiency of existing wastewater systems must be increased. To maximize wastewater recovery and beneficial use, wastewater management services must be extended at an accelerated rate to the unserved secondary cities and communities in MENA.

Necessity and promotional efforts over the past two decades led to wide recognition of the importance of wastewater as a potential water source in MENA. Yet this potential water source is not fully utilized and it continues to pollute the scarce water resources. The problem lies in the way wastewater is managed and recycling is perceived.

For a long time centralized wastewater systems have been the preferred choice of technical service providers, consultants, planners and decision makers and are seen as the ultimate solution for the wastewater problem. The standard large, water dependant and capital intensive sewer networks are built to transport domestic wastewater to central treatment from which the treated effluent is disposed on land or in wadis, rivers, or the sea.

Centralized wastewater management practices are based on models developed in wealthy and water-rich societies and their design standards and practices are based on the following three assumptions:

1. Plenty of water is used by residents to ensure sewer flushing and self cleansing;
2. A water body receives the treated effluent and the effluent quality standards of BOD/COD/SS evolved so as not to exceed the self purifying capacity of the water bodies;
3. There is enough money to build these costly systems

The first two assumption are naturally not valid in arid countries. The high cost of centralized systems renders them unaffordable and their dependence on water as a transportation medium makes them problematic and inappropriate in arid countries. Experience with centralized systems in MENA is far less than desirable. Sewer networks are overloaded and often suffer from siltation and blockages due to the low water consumption where water supplies are intermittent. Treatment plants, often added years after the construction of the sewer networks, are overloaded and poorly maintained. The quality of their outputs falls short of expectations for the intended pollution control and recycling.

Disposal and not reuse is the primary objective of conventional centralized wastewater management. The effluent quality standards expressed in (BOD/COD/SS) terms and the treatment processes designed to achieve them are not always compatible with reuse quality requirements. The physical configuration of a centralized wastewater system is not always compatible with the location of wastewater reuse opportunities. Consequently, wastewater reuse is often concentrated in agriculture at distant locations from the generating communities. Wastewater reuse opportunities within and around the generating communities in agriculture and in landscaping, in lieu of the best quality and most expensive drinking water, are missed.

For reasons of the economy of scale, the large systems have been promoted. There is growing evidence however that while large sewerage treatment plants gain some economies of scale the entire wastewater management system gains bigger diseconomies because of the cost of the sewers networks to collect waste from greater areas (Hawken P. *et.al.*, 2000). A study in Adelaide, Australia, found that the conventional centralized design was at least ten fold larger than an economic optimum (Clark and Tomlinson, 1995). The centralized systems place lesser investment in the treatment plants and greater investment in the non-value adding sewer networks which account for about 90% of the entire wastewater management systems.

In MENA and other arid areas, environmentally responsible wastewater management services must be developed within the constraints of water resources. Wastewater services must accommodate the water efficiency measures and wastewater generation must be reduced. Efficient and robust systems must be identified and employed to stop further degradation of water quality. Every drop of wastewater must count and therefore wastewater systems must be designed for recycling as a primary objective not only safe disposal. The main design criteria must include the nature, location, and quality requirements of reuse opportunities. Different reuse applications require different effluent quality. Revised effluent quality requirements must ensure safe reuse and ensure smooth functioning of the reuse application system. The BOD/COD/SS terms alone may not always be valid. Designing for reuse dictates the nature and layout of the collection system, the location of treatment plants, the effluent quality requirements and the treatment processes and technology required to achieve them.

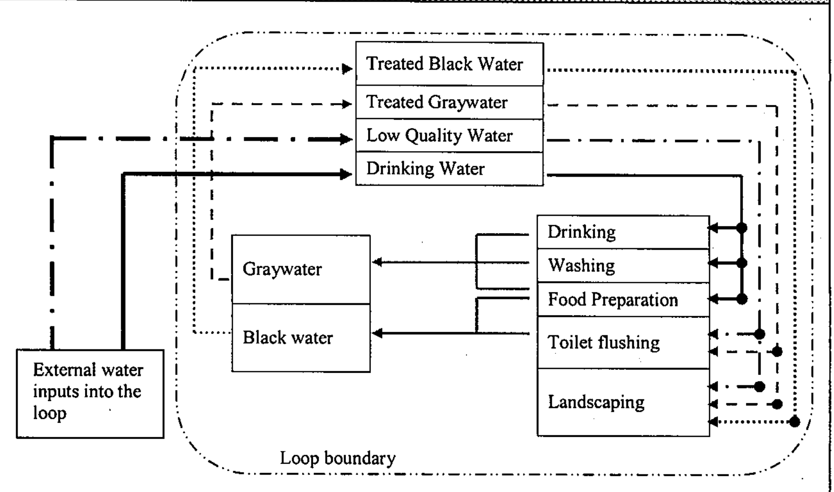
There is a growing debate (Bakir, 2001; Hedberg, 1999; Widerer & Schreff, 1999; Otterpohl et.al. 1997; Butler & MacCormick, 1996) that small decentralized wastewater systems at the scale of a household, or neighborhood can efficiently deliver at much lower cost the intended benefits of wastewater management which are: the protection of public health; stopping pollution of the community environment and the water resources; and maximizing the recovery of water for beneficial use Small decentralized systems facilitate accelerated and environmentally responsible extension of wastewater services which are robust and efficient. The necessary domestic water conservation efforts can be accommodated and the water inputs in wastewater transportation can be reduced, eliminating the non-productive and unnecessary consumption of freshwater in waste transportation. Investment in pollution control can be made more efficient and modular, site tailored and capital efficient wastewater systems are added when necessary. By managing wastewater closer to the source, they place greater investment in reliable treatment works than in non-value adding sewer networks. The environmental risks associated with large schemes are reduced by isolating the problem rather than centralizing it. Wastewater reuse opportunities can be increased within and closer to the source in the household, neighborhood and community where the value of water is highest. The community needs can also be met for better surrounding environment, habitat, trees, and economic productivity.

The technologies are well developed and tested. Greywater can be separated and used for household landscaping with minimum treatment and possibly for other non-potable application, such as toilet flushing, but with more investment in treatment. Total onsite wastewater management and recycling systems may include a septic tank followed with further treatment in intermittent sand filters, subsurface constructed wetlands or reed beds. Highly efficient and compact aerobic treatment plants are also available. When total onsite management becomes not possible due to prevailing site conditions or increased development density, onsite systems can be upgraded. Modular wastewater systems can be built using the lower cost and less water intensive settled sewers to collect the partially treated wastewater effluent from septic tanks to neighborhood or community treatment facility after which the effluent can be brought back for beneficial reuse.

The closed water loop concept

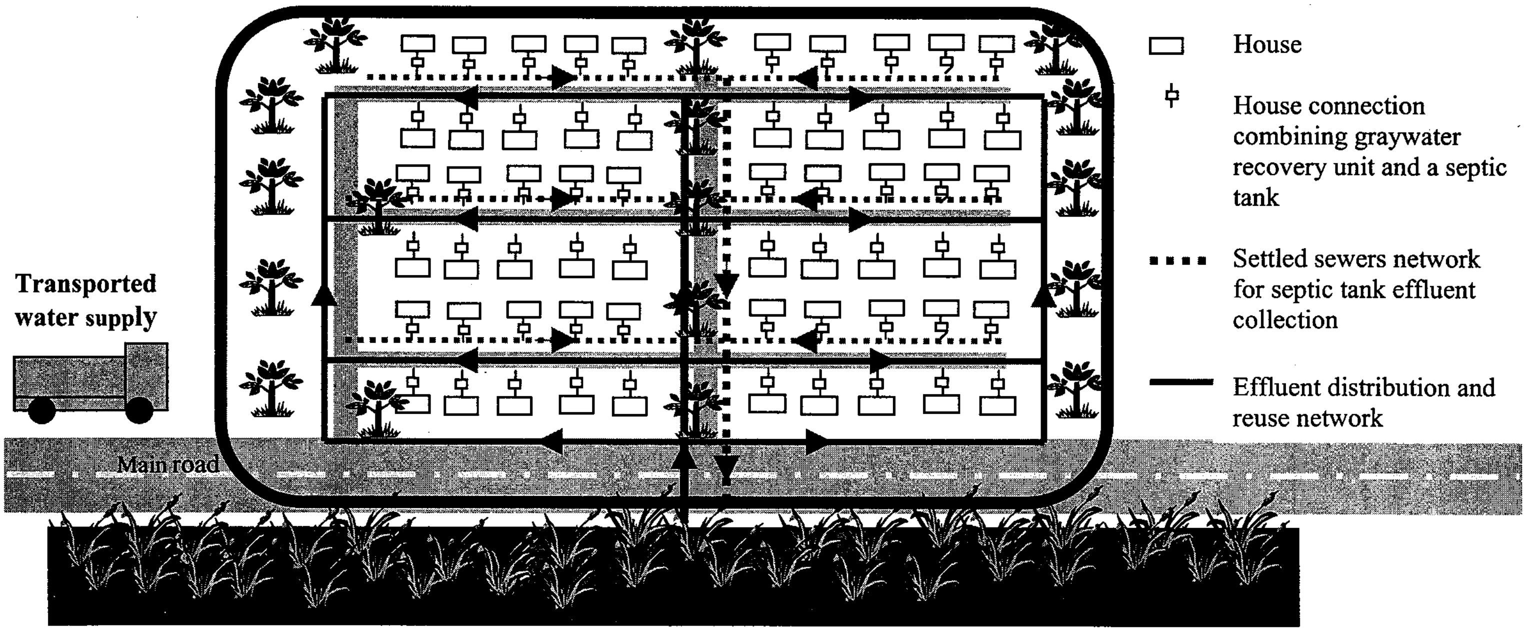
The closed water loop concept, graphically illustrated in figure 5 for a residential building and in figure 6 for a residential neighborhood, offers a practical model that demonstrates the principles of water demand management approach. At the scale of the household, neighborhood, community, industry, or institution water can be managed as a closed loop. Water inputs, of various qualities, can be brought from outside the boundaries of the water loop for the various water applications where the water quality is matched with the intended application quality requirements. Every drop of water can be used at least twice before it is sent out of the loop. After water is used, the generated wastewater is segregated according to the level and type of contaminants it contains. The wastewater streams are treated and the recycled water is kept in the loop and used in the appropriate applications requiring lesser quality water.

Figure 5: A closed water loop for a residential building



At the scale of the household and residential buildings, the highest quality water is reserved for drinking and food preparation and hygiene requirements. Water abstracted from low quality shallow aquifers can be used for landscaping or toilet flushing. Brackish water for example can be used for toilet flushing. Greywater is separated, treated, and kept in the household water loop for landscaping or toilet flushing. Wastewater from the toilets and kitchens can be treated in a septic tank followed by a sand filter or constructed sub-surface reed bed or wetlands. The sub-surface bed can be built within the household landscape and used to grow ornamental plants and others to aid the treatment process. Sub-surface irrigation can be used to prevent the contact between the treated wastewater and people. Subsurface irrigation networks can be built to irrigate trees and to create a pleasant environment and a habitat for birds.

Figure 6: Sustainable Development: A Closed Loop System for a Residential Cluster



Subsurface constructed wetland for septic tank effluent treatment.

Rational planning
Rational planning processes and management practices are needed to translate the principles of water demand management into action. The planning processes entail:

1. An assessment of the available water resources (current and potential) and demands on water (past, current and future) by all water user groups to provide answers to the following questions:
   a. *Does the water use pattern support the public interest and the overall socioeconomic objectives of the society?*
   b. Does the quantity and quality of water use match those of the available resources?
   c. Is water used efficiently by all water users groups? Is the actual water use reasonable, in terms of both quantity and quality, and as judged by accepted standards?

2. Allocating water, in quantity and quality, amongst the competing water using groups to ensure meeting the public interest as defined by the national socioeconomic objectives
   a. Establishing water efficiency targets for each water users group
   b. Identifying water efficiency performance indicators to monitor the performance of each water using group
   c. Establishing an incentive or disincentive system to enforce the demand management approach
   d. Designing and executing sustained water efficiency programmes integrated within the operation of each water using group
   e. Monitoring the performance of the water efficiency programmes of each user group and undertaking the necessary adjustments.

Water management institutions must also recognize that investment in water demand management is an effective investment in the country's water resources which can lead to better returns than investment in new water supplies. Water suppliers must play a proactive role not only investing in improving their efficiency in producing, delivering and distributing water, but also investing in ensuring that their customers use water efficiently.

CONCLUSIONS

Water shortages in MENA are caused by structural causes of nature, climate, and population pressure. Water shortages are further worsened by non-structural causes brought about by the way water is managed. The prospects are grim for development of accessible and other sources of water at affordable cost. The supply driven approach of continued search for additional water sources accompanied by inefficient and unwise use of water, inadequate pollution control, and over abstraction will bring the water situation in many countries of MENA to crisis. Some countries are already in crisis.

There is no other region on earth where the need is so acute for a major shift in water policies from the supply approach to the demand management approach within integrated water resources management. The search for additional water sources should not begin until the perceived demands on water are challenged and all possibilities are exhausted for manipulating the demands in order to match them with existing supplies. Demand can be manipulated through: efficient allocation in quantity and quality to the competing users of water (agriculture, industry, and domestic) to ensure that water is used wisely and optimally for the public interest; efficient water use by all users to eliminate wasteful consumption and reduce consumptive use of water; and sufficient and efficient environmental protection for pollution control and maximized safe recycling. The management tools, enabling strategies, technologies and innovations are available and well tested.

There is a wealth of experience in water demand management in MENA. The Bahrain experience demonstrates that investment in water demand management is a more cost effective strategy than investment in water resources which defers the need for urgent expansion of the water system. The Cyprus experience demonstrates innovative management approaches where the water authorities invest not only in increasing the efficiency of their service delivery systems but also in ensuring that consumers of use water more efficiently. In Tunisia, the urban water demand management programme achieved significant and sustained reduction in municipal water consumption. Experience in those countries shows that only comprehensive, sustained, and proactive interventions can achieve lasting results. Sporadic, ad-hoc and poorly targeted water conservation and education drives alone rarely achieve results.

The shift to water demand management starts with an understanding of the non-structural causes of water shortages and recognition at the highest policy level for the need for such a shift. Institutional and sector reforms that are supportive to the water demand management shift are necessary. Rational planning processes are needed to ensure that water is developed, allocated, used, and protected in ways that ensure efficient, sustainable and beneficial use of water in the public interest.

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Determination of Ground Water Aquifers along Wadi Numan, Saudi Arabia

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DETERMINATION OF GROUND WATER AQUIFERS ALONG WADI NUMAN, SAUDI ARABIA

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Abstract

In the recent years, the demand for water consumption has rapidly increased. The search for new water resources triggered a new wave of ground water exploration activities, especially in arid region such as in Saudi Arabia. Although, the geophysical exploration methods have been improved and developed in recent years, a majority of the techniques are difficult to use because of their costs and effort they require. In order to overcome these difficulties, it is advisable to first conduct regional geophysical studies for the area along the different existing valleys in order to select the most structurally and hydrological promising zones.

The present study deals with using geophysical methods for defining the most significant structural settings for water accumulations along Wadi Numan which lies at the east of Makkah Al Mokarramah, K.S.A. The study area is located between latitudes 21° 17'- 21° 24′ N and longitudes 40° 00′ – 40° 10′ 55" E. The area under investigation forms a part of the Arabian shield of the western Saudi Arabia. Accordingly, igneous and metamorphic rocks cover the study area. In the upstream of Wadi Numan, the escarpment is a conspicuous structural feature. The valley itself is structurally governed by different systems of major and minor faults are dominant in Wadi Numan and adjacent areas.

Total magnetic intensity measurements were conducted on the ground along 30 km of the Wadi Nu'man. The results of this survey indicated that the area between Wadi Rahgan and south Arafat zone is considered as a significant structural water catchment zone. To emphasis this results, 25 vertical electrical soundings (VES) were conducted along two E-W parallel profiles to define the relation between structures and water distribution. In addition, three seismic profiles was conducted in certain zones to delineate the main structures elements which control the water drainage in the selected area.

INTRODUCTION

The extreemely arid zones such as Saudi Arabia are charcterized by very little, unpredictable, and irregular occurrence of preceptation that are very extensive during the local storms. This delineate that there are no permenent streams in proper sense. Therefore, it is nessessary to conserve and develop every single drop of water in these zones.

The present study includes the eastern part of Wadi Numan which extends beteen the foothill of the El-Hada mountain and south of Arafat. This area is bounded by latitudes 21° 17'- 21° 24′ N and longitudes 40° 00′ – 40° 10′ 55" E (Figure 1). It is considered as one of significant basins in Makkah AL-Mokarramah region. For a long time, Wadi Nu'man is considered as a potential freshwater source for the holy capital.

The escarpment of Al-Hada mountain, a conspicuous structural feature, is located at the upstream of Wadi Nu'man. Wadi Nu'man itself is structurally governed by different systems of major and minor faults which are dominent in the area. Figure (2) shows the main topography of Wadi Nu'man area and its turbutaries.

The area under investigation forms a part of the Arabian shield of the western Saudi Arabia. Accordingly, igneous and metamorphic rocks cover this area. Except for the strips which are occupied by wadis, the study area is covered by igneous and metamorphic rocks (Brown et al., 1963). The basement rocks are intensively jointed, breciated and faulted. These fractures and fissures create conduits for downward percolation of water. However, in this study, the basement rocks are considered to be impervious surfaces. The structure of these rocks greatly influences the drainage system Mohammed (1985). Unconsolidated deposits, represented mainly by alluvium cover, these basement rocks. These wadi alluvium are composed of sand and gravel alternating with silts to boulders and represent the main aquifer within Wadi Nu'man (Figure 3).

Jamman(1978) studied the wadi nu'man by using vertical electrical sounding the determine the depth ofwater table and bed rock. This study concluded that Wadi Rahgan and Wadi Arar are important tributaries feading the main wadi course.

The present study deals with using Magnetic, electric and seismic refraction methods for defining the most significant structural settings for water accumulations along Wadi Numan. Total magnetic intensity measurements were conducted on the ground along 30 km of the Wadi Nu'man. The results of this survey indicated that the area between Wadi Rahgan and south Arafat zone is considered as a significant structural water catchment zone. To emphasis this results, 25 vertical electrical soundings (VES) were conducted along two E-W parallel profiles to define the relation between structures and water distribution. In addition, three seismic profiles was conducted in certain zones to delineate the main structures elements which control the water drainage in the selected area.
The integration between ground magnetic, resistivity, and seismic refraction methods is used to obtain the most useful results.

TOTAL MAGNETIC INTENSITY METOD

Field survey and data presentation

The main purpose of appling magnetic survey to ground water studies is to determine of the subsurface relief of basement rock underlying the water-bearing sediments. The study of basement - rock configuration generally involves determining the depth to the surface of the basement at several points which leads, to determining the relief of the basement surface.

According to geology, the lithological composition of Wadi Nu'man runs through different types of rock units with different properties. Each of these rock units has a special magnetic character. In addition, the subsurface structural features, faults, fractures, and dykes all have some distinctive effects on the total magnetic field. Therefore, the main purpose of the magnetic survey is to explore subsurface structural features along Wadi Nu'man.

The total magnetic intensity survey was conducted along 32 km of Wadi Numan. The magnetic survey started at Jabel Al-Hada to the east of Arafat and ended South of Arafat. The station interval distance used was 30 m. Two units of the proton precession magnetometer model Envi-Mag, Scintrex made, were used. One unit recorded the variation of the total magnetic intensity along the profile. The other unit used to record the dirurnal variation of the main magnetic field intensity of the earth's magnetic field and its accuracy is about 0.1 nT. Accordingly, The corrected total magnetic intensity measurements along Wadi Nu'man are presented as total magnetic intensity curve.(Figure 4).

Data analysis and interpretation of the total magnetic intensity data:

The frequency of the magnetic anomalies can be used to reveal the depth of the basement rocks. The high frequency anomalies are indicative of shallow depth of the basement surface. On the other hand, low frequency (smoothed) magnetic anomalies indicate that the basement rocks are covered with thick sedimentary cover. Accordingly, the magnetic method can be used to locate the main structural zones which control the groundwater distribution and can be used to determine the relative thickness of the sedimentary cover which is usually the main target in the hydrological studies.

The total intensity magnetic curve (Figure 4) delineates that there are distinctive changes in the amplitude and frequency along of the profile. These changes return to the variation in depth levels lithologic, and structural features of the basement rocks beneath this profile. The depth of basement surface along this profile was determined by using Filon Foruier frequency technique (Sadek, 1987). The average depth of basement surface was calculated from the slope of the linear segment of the frequency analysis curve (Figure 5). The window interval used for depth determination was 600 m. In addition, the ground surface elevation above sea level at each location where the depth to the subsurface basement surface was estimated was obtained from topographic maps. Both elevations and depths of the basement data are ploted againist their corresponding locations on the profile (Figure 6). Figure (6) also shows the variations in the thickness of the sedimentary cover. In addition, the amplitude and frequency variation along the total magnetic intensity curve (Figure 4) shows that the total magnetic intensity curve can be subdevided into seven segments. Each of these segments of curve indicates that the depth and lithological features of the sources of magnetic anomalies beneath each of these zones are different. Table (1) shows the results of the average depth determination of the interpreted structural zones which can be described as follow:

The first zone extends about 8950 m. The magnetic amplitude along this zone ranges between 3946 and 40791 nT. The magnetic character of this zone is related to the basement rocks outcroping along this part of the profile. Mainly, these types of basements rocks are similar to the rocks which located under the sedimentary cover along Wadi Nu,man. Therefore, the variations in the magnetic response related to the depth of these rocks from the surface of the Wadi.

Table.1. Results of depth determination of total magnetic measurements

Zone No.	Distance in m		The average depth of basement in m from the ground surface
	From	To	
Zone I	0	8950	0
Zone 2	8950	12500	54
Zone 3	12500	16500	38
Zone 4	16500	20600	56
Zone 5	20600	24000	48
Zone 6	24000	26500	77
Zone 7	26500	32000	69

The depth of basement surface in second zone is about 54 m and the magnetic intensity amplitude ranges between 39650 and 40075 nT. This zone occupies the distance from 8950 m to 12500 m along the profile, and is followed by the third zone. Zone 3 has high frequency magnetic character extends between 12500m and 16500 m. The average depth of basement surface along this zone reaches 38 m. The fourth Zone occupies about 4 km starts at a distance 16500 m to 20600 m of the profile and is characterized by high range of low frequency magnetic intensity amplitude. The average depth of basement surface reaches 56 m. The magnetic response may be related to basic nature of the basement rocks along this zone. The Fifth zone is simmilar to the fourth zone but it is charactized by its relatively higher amplitude of magnetic intensity (40360 nT to 40992 nT). The high amplitude may be related to the presence of a fualt between zone zone 4 and 5. The average depth along this zone reaches 48 m. This zone occupies about 3.5 k of the magnetic profile starting at distance 20600 m. Zone 6 is charactirized by a relatively higher basement surface average depth value of 77 m. The magnetic intensty amplitude of zon 6 ranges from 40882 to 40992 nT. This indicates the presence of a fault between zone 5 and zone 6. The presence of fault is highly significant in water exploration because they control the groundwater flow beneeth the surface of the Wadi. The last zone of the profile is also characterized by deeper basement surface of 69 m. Accordingly, zones no. 6 and 7 are considered here as the most important zones from the point of veiw of groundwater exploration. Therefore, these two zones are selected to carrying out further investigations using more sofisticated geopgysical techniques to evaluate their ground water resources.

VERTICAL ELECTRICAL SOUNDING METHOD

Field survey and data presentation

Vertical electrical sounding survey (VES) was conducted using Shlumberger array at 24 sites distributed along two (E-W) trending profiles (Fig. 2). The VES specifications were selected as seven measurements per decade to obtain reasonable data continuity, while half current electrode spacing (AB/2) ranges from 1 m to 300 m. These specifications allow considerable depth penetration beneath each sounding site. The survey equipment used is a modern 1200 Watts D.C. resistivity meter model ELREC-T (IRES- French made).

The data were reduced and analysis and each vertical electrical sounding curve was first compiled to describe the apparent resistivity (ρ_a) from its different segments obtained during field measurements. The continuos sounding curve was then smoothed and digitized to produce a six (ρ_a) readings per decade of half the electrode spacing (Fig. 7-a). The digitized data of the reduced field curve were inverted and interpreted using the inversion technique developed by Zohdy (1975) to obtain the equivalent layer models (n-layered model, Fig. 7-b).

The n-layers models of the different soundings were used to construct the subsurface true resistivity contour sections along each of the two profiles (Figures. 8 & 9). The contour values represent the logarithmic values of the resistivity.

Interpretation of vertical electrical soundings (VES) data:

In general, the variations in electrical resistivity can be used to differentiate the subsurface formation into different characteristic zones of different lithology and water saturation. The careful examination of northern and southern subsurface resistivity contour sections (Figs. 8 & 9) provides details about subsurface lithology, structure and ground water occurrences.

The northern subsurface resistivity contour section (Figure 8) shows the presence of an upper layer of unconsolodated sediments which is characterized by high resistivity values. This layer is followed by a low resistivity layer. Therfore, the low resistivity layer is believed to be fully or partially saturated with ground water. As clearly revealed in Figure (8), the depthto the water saturated layer is about 20 m. The thickness of this layer beneath VES3 to VES6 ranges between 45 m beneath VES8. The water saturated layer thickness decreases gradually as we move further east toward VES10-VES12. The resistivity contours of the section indicate that wadi Numan is affected by N-S structure extends between the VES6 and VES8 locations.

The southern subsurface resistivity contour section (Fig. 9) shows similer results to those of the northern section with the top of the water saturated layer located at a depth of about 10 m. The thickness of the water water saturated layer ranges between 30-50 m beneath most of the profile at VES1 to VES6. Its thickness reaches a maximum of about 65 m beneath VES11.

The northern and southrn resistivety contour sections (Figures. 8 & 9) indicate that wadi Numan is affected by A N-S structural system of faults controlling the ground water flow under the surface of the wadi.

SEISMIC REFRACTION METHOD

Field survey and data presentation

The seismic refraction technique is more suited for shallow investigation particularly in engineering and hydrogeological applications. Therefore, it is used in the present study to provide information concerning the velocities of elastic waves and to determine the depth, shape of bed rock, and to some extent, the lithology of inferred refractors (e.g., Sherif and Geldert, 1982 and Haeni, 1986).

The subsurface seismic refraction technique furnishes a convenient approach to the in-situ determination of P-wave seismic velocity at the assigned three profiles in the present study area. Moreover the seismic velocity in rocks depends on several factors, including porosity, lithology, cementation, depth of burial, pressure regime, interstitial fluids,....., etc., (Sheriff and Geldert 1982). In the present study, where the sediments overlie basement rocks, the seismic method is used to determine the thickness of these sediments, and irregularity of the basement surface, which has a special hydrogeological interest. The sediments occur in the form of channel filled with silt, sand and gravel. The seismic velocity in saturated sediments (about 1.5 km/sec) is generally higher than that in dry sediments (less than 1.0 km/s) so that the zone of saturation acts as a refractor.

The seismic recording system used in the present study was the Bison-7024 digital instrument floating –point (DIFP) signal –stacking seismograph. It is a 24-channel seismic data acquisition system (Bison 7000 series, 1990). Vertical component geophones were used in the present study to pick up P-wave arriving at the earth's surface. 7-kg sledgehammer and elastic wave generators (EWG-II), 250-kg weight drop were used for P-wave generation.

Three seismic profiles were selected for conducting the seismic survey (Fig. 2) according the results of magnetic and resistivity surveys to investigate the stratigraphic succession of alluvium and depth of basement surface. One of these selected seismic profiles, S1, (Fig. 2) was conducted along a distance of 450 m (oriented S to N) in the southern side of sixth structural zone. The second and third seismic profiles (S2 & S3) extend from E to W to intersect the structural zone boundary between the zone 5 and zone 6 at both suothern and northern sides of Wadi Numan. The seismic refraction data acquired in the present investigation were inverted using the seismic refraction inversion software "SIPT-2" (Rimrock Geophysics Inc., 1993). The inversion algorithm uses the delay-time method (Pakiser and Blank, 1957) to obtain a first approximation depth model. It is then trimmed up by a series of ray tracing and model adjustment iterations to seek minimize the discrepancies between the field measured arrival times and the corresponding times traced through the 2 ½ - D cross sectional depth model (Scott et al., 1968; and Scott and Markiwicz, 1990). Along each of the three seismic profiles, the subsurface interpreted section is obtained (Figs. 10, 11 & 12). The interpreted sections show the characteristic layering along each profile. The relations between the surfaces of layers show the subsurface structures. The calculated seismic velocities of these layers define their lithological properties.

Interpretation of Seismic Refraction Data:

The subsurface section (Fig.10) which was obtained from the seismic refraction measurements at the first site S1 (Fig. 2), shows that four characterized layers overly the basement. The upper three layers have low seismic velocity ranged from 315 to 880 m/s, respectively. The total average thickness is 30 m. These values of velocity reveal dry, unconsolidated materials with different grain sizes (alluvium). In the southern 120-m of the profile, this dry formation overlies directly the basement (with velocity 4845). However, in the northern part of the profile, the basement rocks is covered by an additional sedimentary layer with seismic velocity in the order of 2245 m/s and average thickness that reaches to 55

m. The seismic wave velocity of this layer indicates that this layer is probably saturated. Accordingly the thickness of sedimentary rocks range between 30m and 85m. Also, the seismic section delineates the existence of an E-W trending fault with vertical displacement about 30 m and dipping apparently to the north.

The subsurface section (Figure 11) which was obtained from the seismic refraction measurements at the second site S2 (Figure 2), shows that two distinctive alluvial layers cover the basement rocks, their seismic velocities are 430 and 1150 m/s, respectively. The velocity of the second layer indicates that this layer is probably wet. The thickness of sedimentary cover is about 22 m in the eastern 300 m of the profile. This thickness increases at the western side until it reaches to 45 m. The variation of depth of basement rocks surface indicates that there is a N-S trending fault with vertical displacement of order of 25 m and dipping apparently to the west.

At the third site, the subsurface section (Figure 12) which was obtained from the seismic refraction measurements of profile S3 (Figure 2), shows that the sedimentary cover of the basement rocks is composed of two different layers, with values of seismic velocity as 320 and 805 m/s, respectively. The velocity of the second layer indicates that this layer is dry (during the survey time). The total thickness of sedimentary cover in the western 550 m of the profile is about 35 m. This thickness increases until it reaches to 45 m at 610 m from the west and decreases to 22 m at 980 m from the west. The variation of thickness of sediments overlying the basement rocks indicates that there is a N-S trending fault with vertical displacement about 13 m, and dipping apparently to west.

CONCLUSTIONS

The present study deals with using geophysical methods to define the most significant structural settings for water accumulations along Wadi Numan as one of the considerable long wadies in the western part of Saudi Arabia.

Regional magnetic survey was conducted along 32 km of Wadi Numan. The amplitude and frequency variation of total magnetic intensity measurements delineate that Wadi Numan can be classified into seven segments. Basement rocks beneeth each of these segments has different lithological and structural features. Also, the depth of basement surface as a source of magnetic anomalies beneath each of these zones is different. The depth of basement along Wadi Numan was found to vary between 38 and 77 m. The results of depth deermination are tested by the comparizon between the depth of basement values which are obtained through well drilling at two different location along Wadi Nu'man, one at coordinates 21 19 547 Nand 40 01 398 E (zone 6)and the other at coordinates 21 21 486 and 40 06 87 E (zon 3).these depth values are 62 and 42, respectively. These values are relatively confermed with the average depth values (77 and 38 respectively) which obtained using magnetic data. This variation in depth indicates that Wade Numan was affected be a N-S fault between each two of these zones. The increasing depth of basement at zone 6 &7 shows that these two zones are the most significant parts along theWadi. The results of magnetic survey indicate that the area between Wadi Rahgan and south Arafat zone is considered a suitable structural water catchment that might contain reasonable amounts of ground water which stream along the Wadi.

Twenty-five vertical electrical soundings (VES) were conducted along two (E-W) profiles extended along both northern and southern sides of the Wadi. Below the surface of these VES profiles there is a thick layer of unconsolidated sediments and characterized by high resistivity values. Underlying this surface layer is a layer characterized by lower resistivity. Iis thickness ranges between 25-50 m on average along the two profiles. It may be fully or partially saturated with ground water.

The interpreted subsurface seismic refraction sections indicate that Wadi Nu'man may be considered as a grabben structure, which represents the main target of water accumulation. The seismic refraction method reflects the presence of the southern E-W trending fault of Wadi Nu'man grabben and delineates its dip direction (to the north) and vertical displacement (~ 30 m). In addition, N-S trending faults cut across Wadi Numan are recorded in two sites at the zone of intersection of Wadi Numan with Wadi Rahgan. One is located in the southern side and the other is located in the northern side of Wadi Numan. These faults dip to the west and have different vertical displacement (13 m at the southern site and 25 m at northern site). These N-S trending faults construct suitable natural environments for water accumulations under the surface of this part of Wadi.

Finally, the present study shows that zone 6 which extends at the west of Wadi Rahgan is the best site for ground water acumulation. Therefore, detailed hydrological and geophyscial studies are recommened at this site for ground water exploration.

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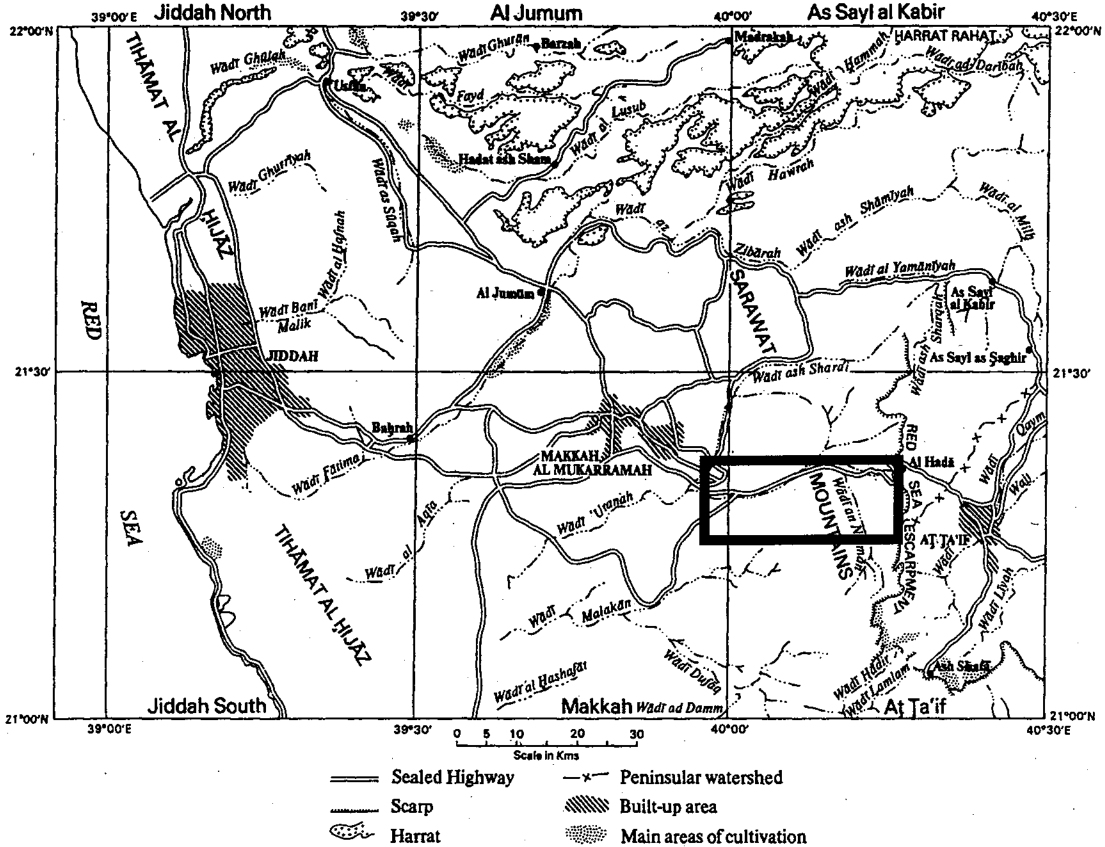

Fig. (1)Locatin of the study area

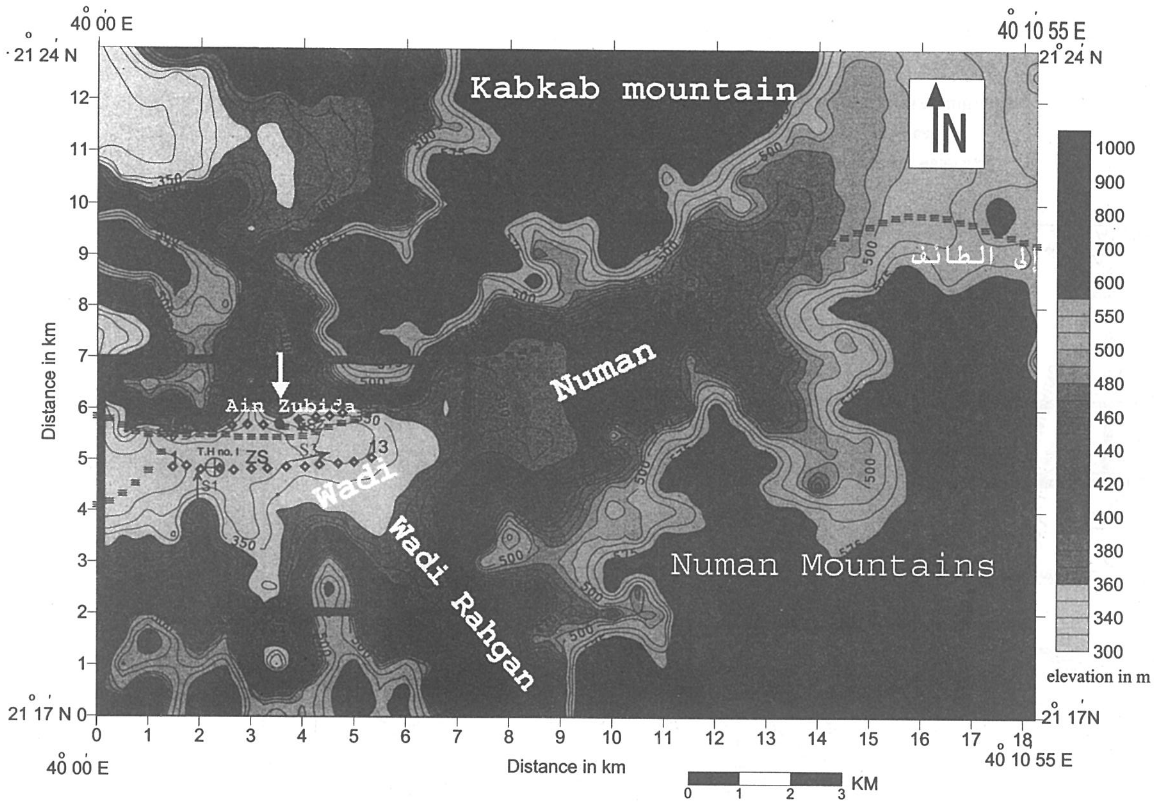

Fig. (2) Topographic map of Wadi Numan

Selected area
VES location
S1 Seismic profile location
Asphaltic road

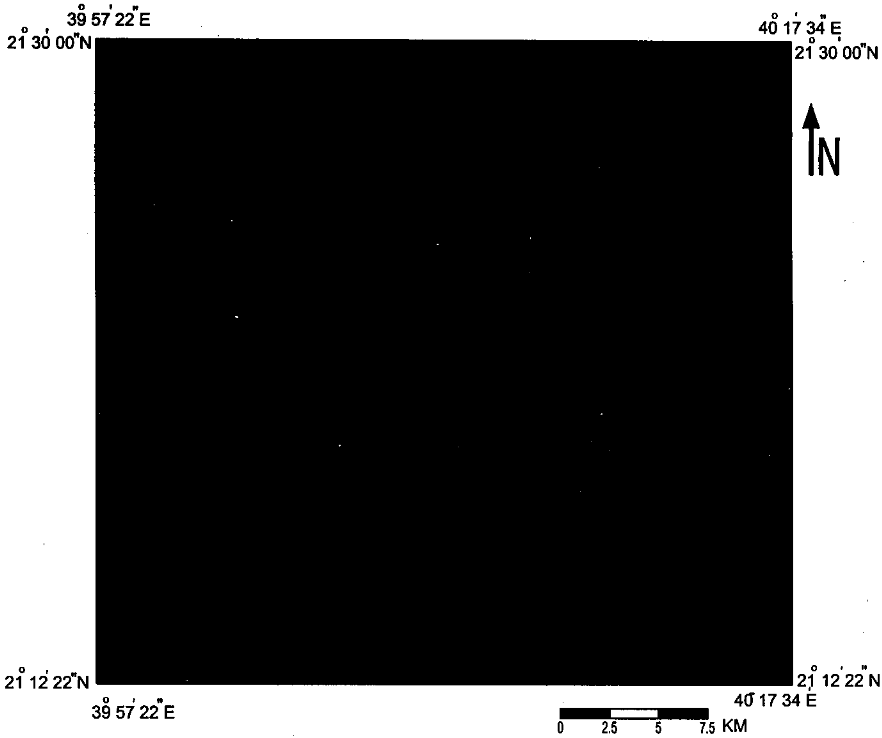

Fig. (3) Geological map of Wadi Numan area. (After Moore & Al-Rehaily, 1989)

Legend

- Undefferentiated Alluvial
- Abbasah Formation
- Paragenesis and Schist
- Numan Complex
- Shamiyah Complex
- Diorite to Quartz
- Metagabbro and Gabbro

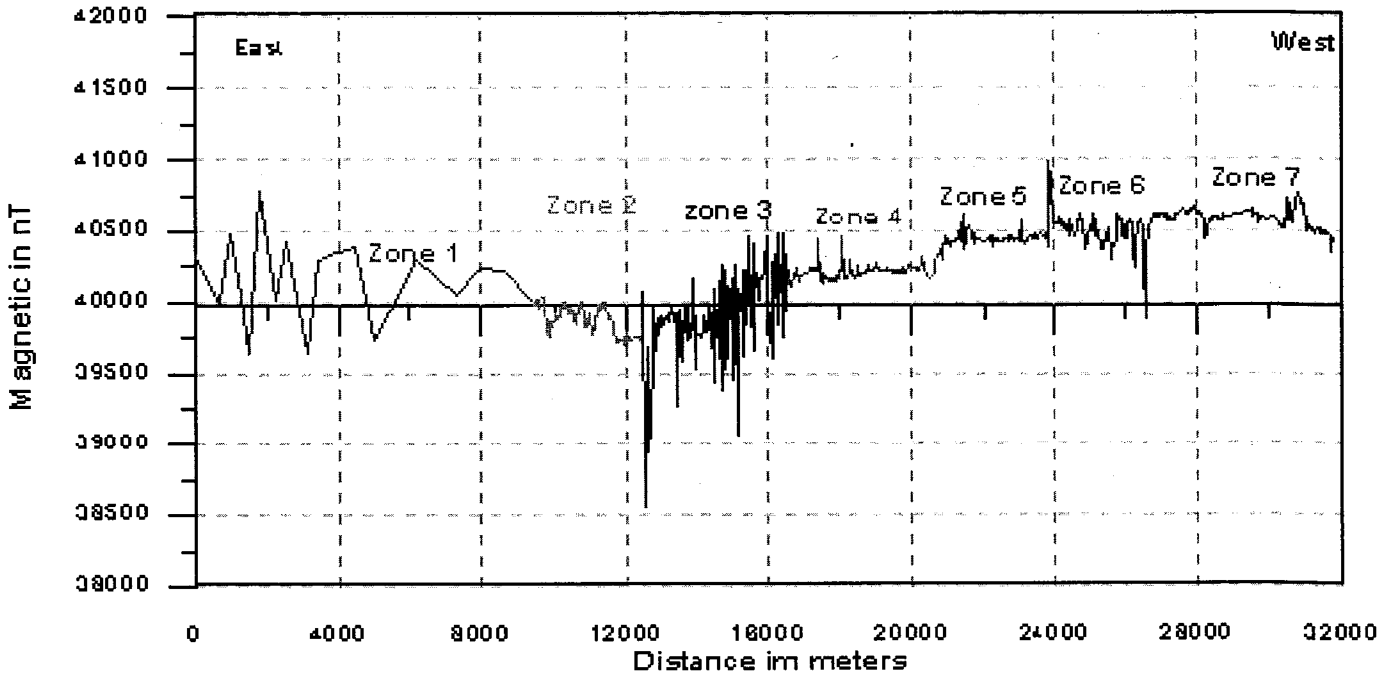

Fig.(4): Total Magnetic intensity profile along Wadi Nu'man

Zone 4 Structural zone

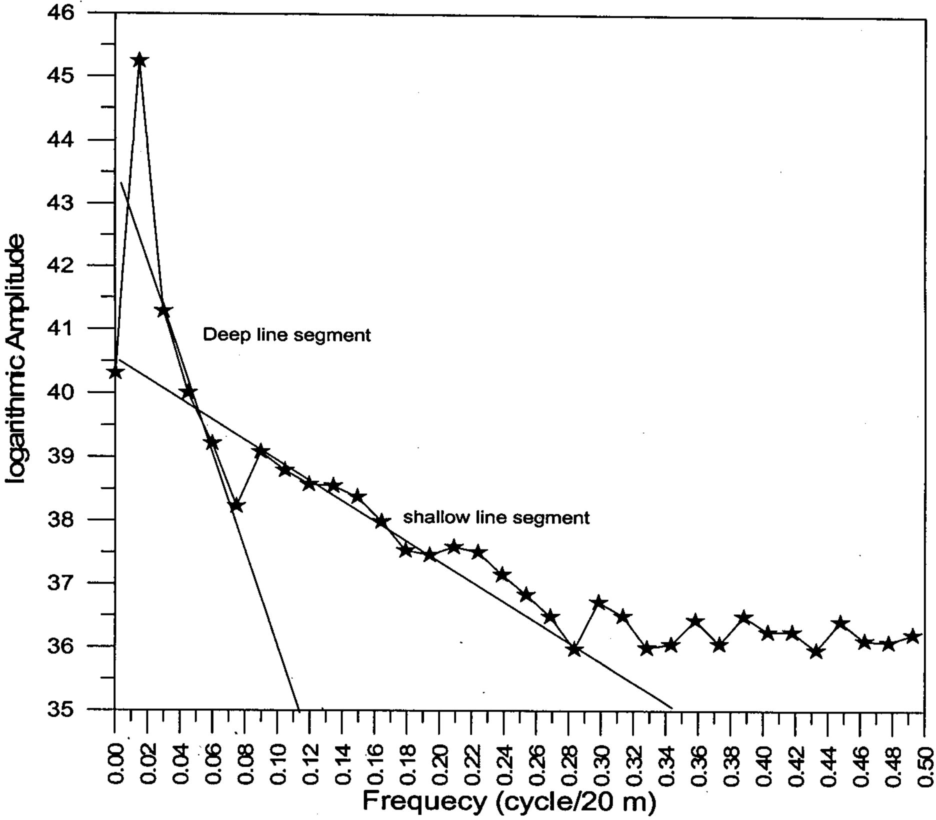

Fig. (5) Frequency analysis curve of the magnetic data.

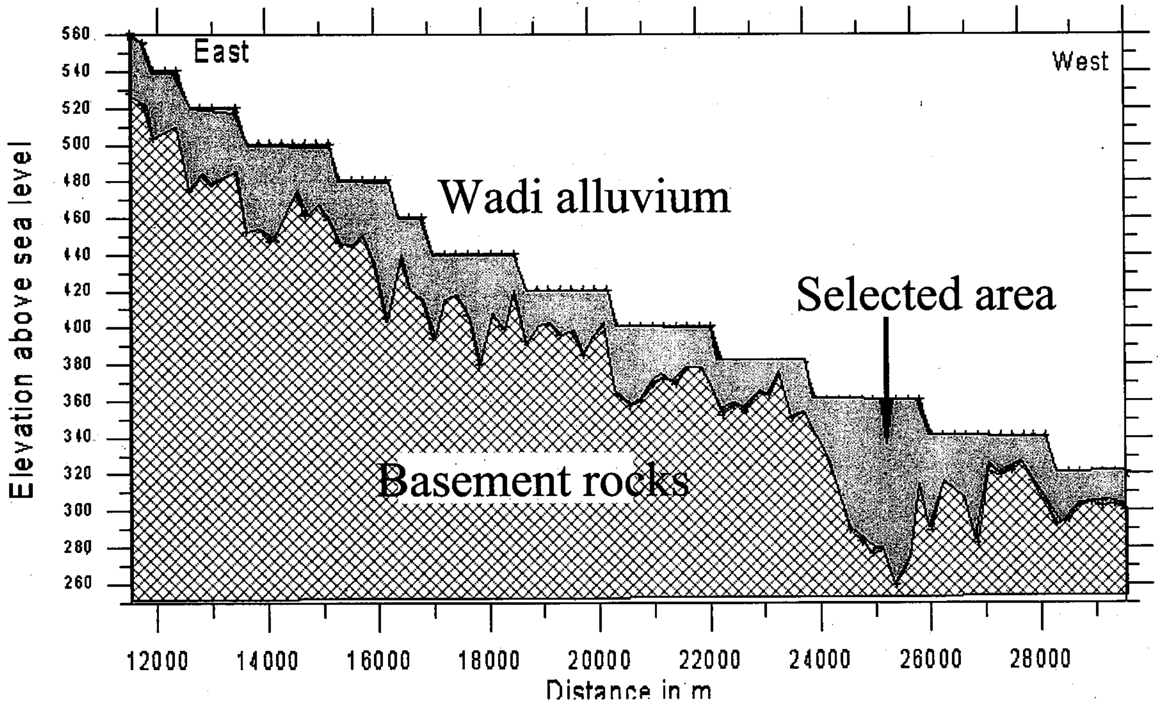

Fig.(6) Interpreted depth of basement surface along Wadi Numan.

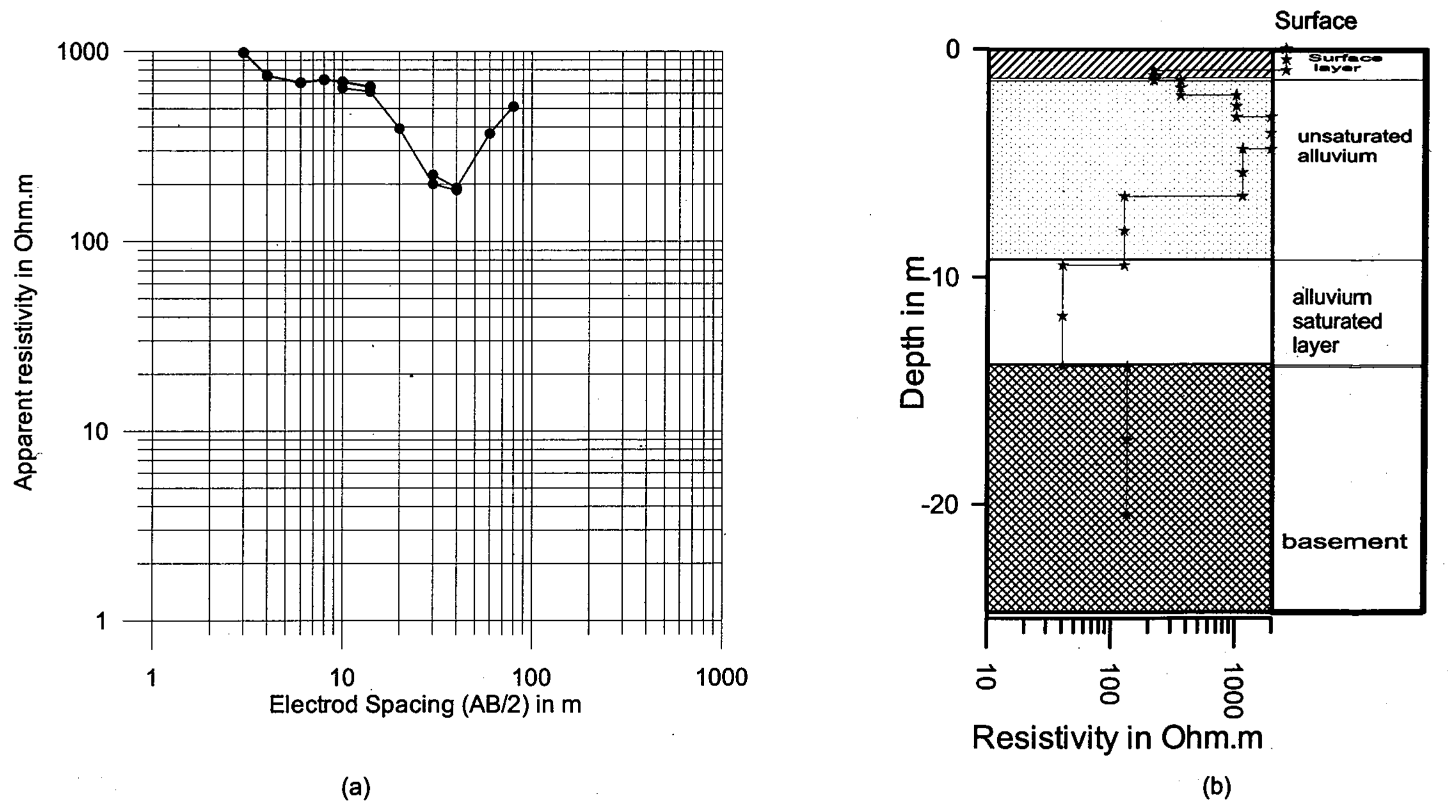

Fig. (7) Vertical electrical sounding field curve (a) and the resultant interpreted geoelectrical section (b).

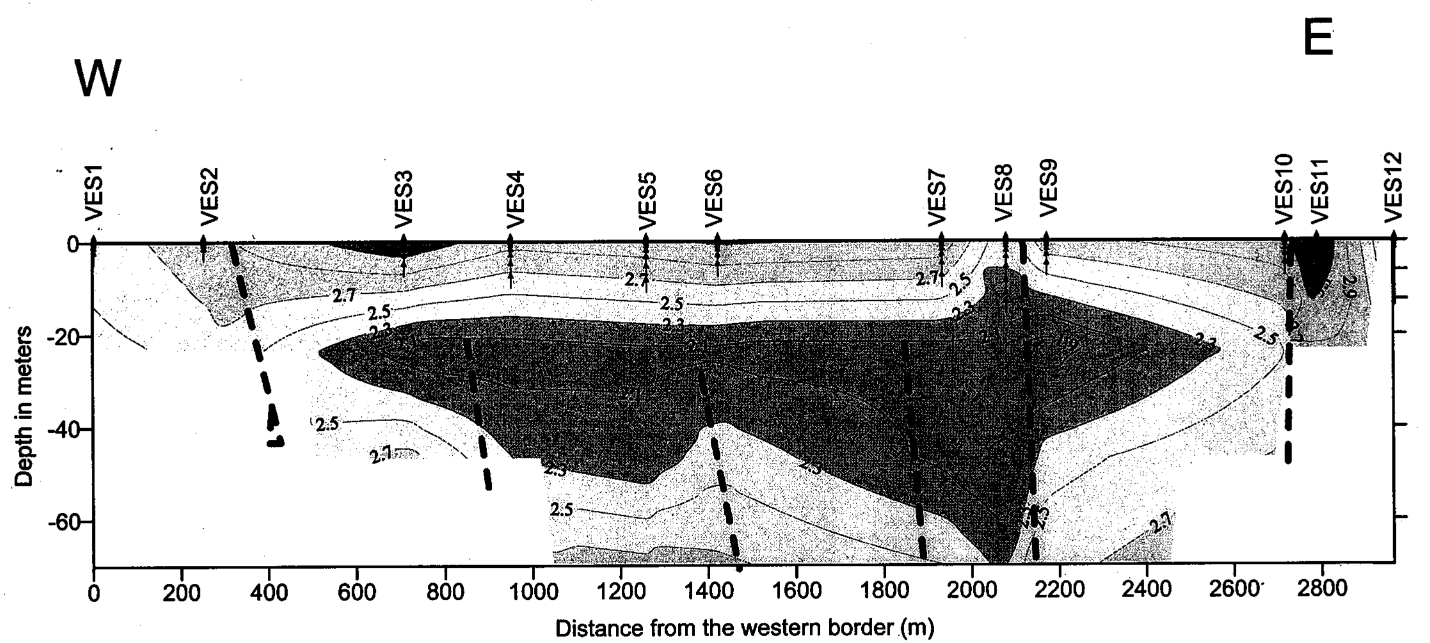

Fig.(8) Geoelectric Resistivity contour section along the northern profile of Wadi Nu'man.

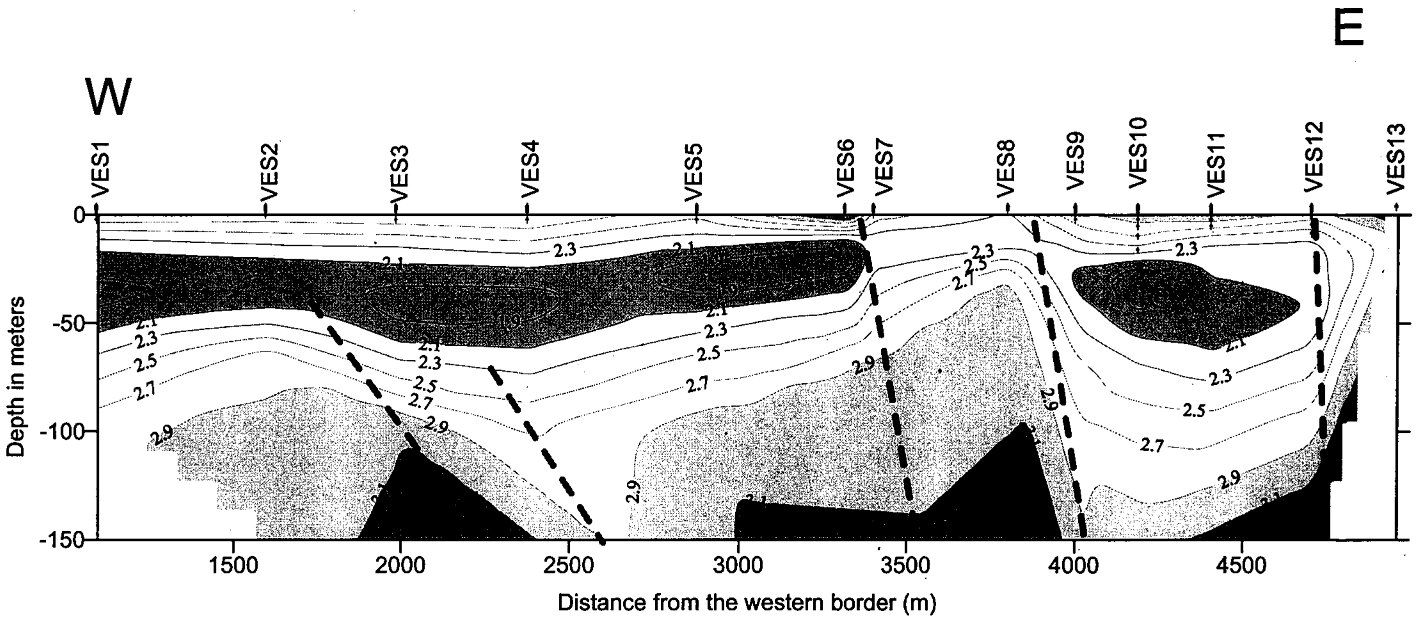

Fig.(9) Geoelectric Resistivity contour section along the southern profile of Wadi Nu'man.

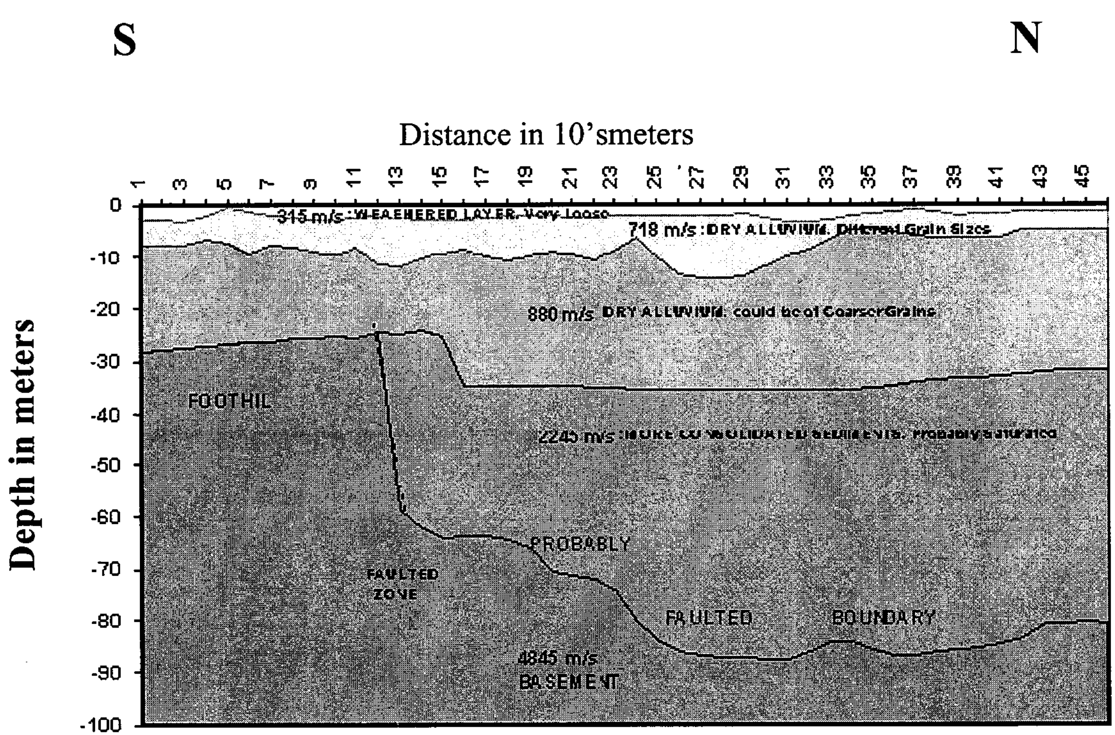

Fig. (10) Geological intrepretation of the seismic section (S1) E to W

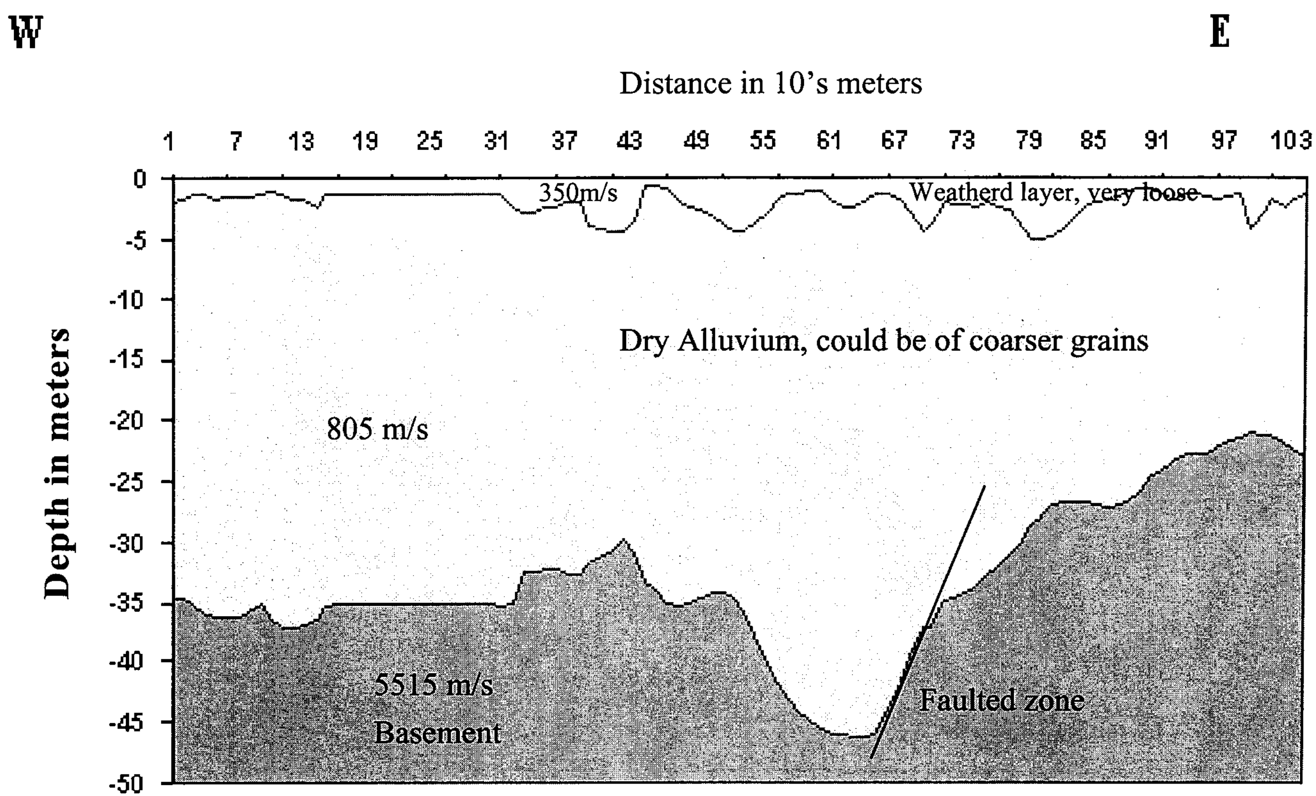

Fig. (12) Geological interpretation of the seismic section (S3)

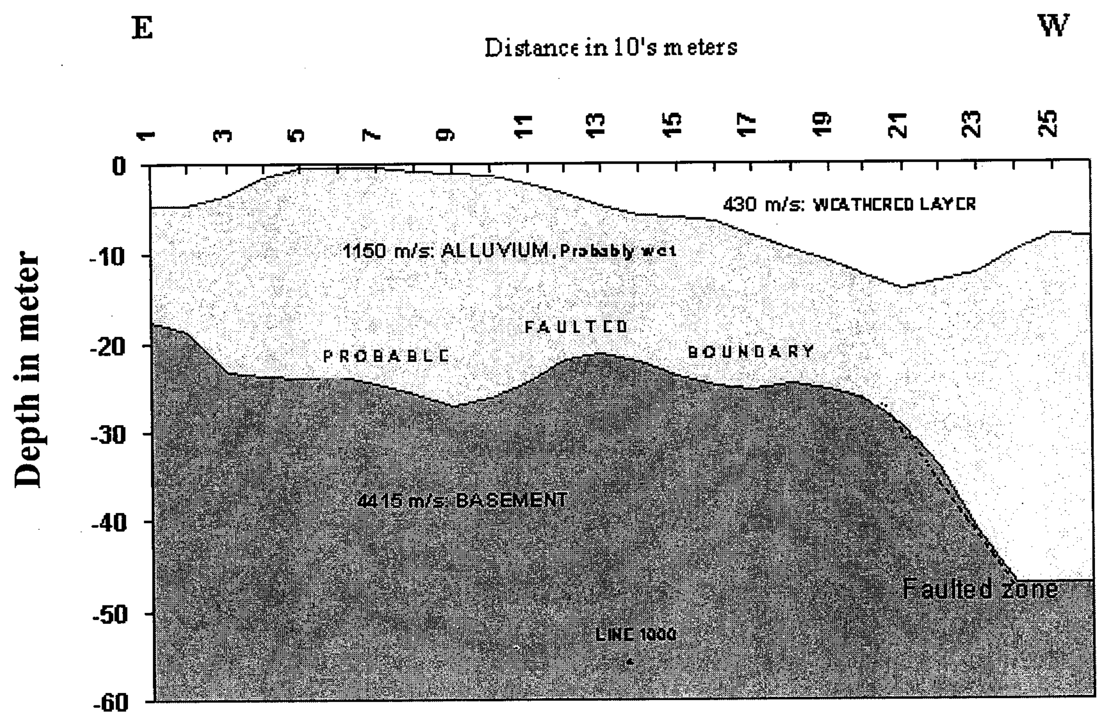

Fig.(11) Geological intterpretation of the seismic section (S2) E to W

Groundwater Supply Control and Management for Large Irrigated Schemes in Al Busayata, Al Jouf, Northern Saudi Arabia

Dr. Yousef A. Al-Rumikani and Saif ud din (Saudi Arabia)

Groundwater Supply Control and Management for Large Irrigated Schemes in Al Busayata, Al Jouf. Northern Saudi Arabia

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Abstract

The optimal management of regional aquifers subjected to intensive withdrawal for irrigation has been attempted for al Busayata, Wadi Al – Sirhan, in Al-Joul, Northern Kingdom of Saudi Arabia. The objective is to control the groundwater level behavior when optimal amount of water required for agriculture activity is abstracted from the aquifer, Al-Busayata area has been selected as a key area for detail investigation of water resources. The aquifers in the area are non-homogenous in behavior. Two tires aquifer system had been considered with different hydrologic properties. The regional stratigraphic and structural geological framework of the area, landform characteristics, metrological parameters and hydro geological milieu has been used for aquifer simulation. The geometry of Al Jouf and Tabuk aquifers were obtained from the drilling and geophysical logs, and wells design data obtained from records. The 3-D simulation was carried out assuming saturated, two tier aquifer, three slices, verticval Exaggeration 1:1, horizontally disposed aquifer, confined, steady state flow, constant time steps, six node triangular prism, 21776 mesh elements, 14250 mesh nodes, constant head boundary in the north and north east, no-flow boundaries in the eastern and western extremes of the study area, southern boundary is considered to be constant recharge boundary. The Water levels were simulated using well discharge data obtained from irrigation projects in the study area with optimization routine runs, iteratively. The transimissivity and storativity as constant and changing the q (draw down). Keeping all other assumptions same only selective pumping was attempted.

The initial heads of 1987 were used and were calibrated using 1991 heads. Five wells namely W12, W43, W70, W81 and W83 were pumped for 20 years, since in these parts the drawdown is minimum. Four trail runs were carried out to arrive at good agreement between observed and calculated values. Consideration of the present water levels and abstraction rates and the resulting heads on comparison with the initial heads show lowering of water level in the area.

The calibrated model has been used for predicting water level of aquifer as influenced by irrigation water requirements of alfalfa, wheat, tomatoes and potatoes for the year 2001. The groundwater level was controlled by selective pumping and managed by simulation. The cropped area for alfalfa, potato, wheat and tomato has been calculated using Landsat TM FCC 432. Using the Penman-Monteith method, the average daily requirement for alfalfa is 94m^3/-day/ha, potato is 54.0633m^3/day/ha, wheat is 53.94 m^3/day/ha and tomato is 69.13 m^3/day/ha. The seasonal water requirements for alfalfa, potatoes, wheat and tomatoes were 2700 million m^3, 34 million m^3, 27.14 million m^3, and 26.086 million m^3 respectively.

The withdrawal of 2787.226 million m^3 water from the aquifers resulted in water level drop of 5 to 20 centimeters.

The groundwater level van be managed using irrigation scheduling and avoiding over irrigation in the irrigated schemes.

It is recommended that the daily crop water requirement for each crop should be calculated for each growth stage and the irrigation schedule shall be prepared to avoid over irrigation and minimize the use of precious water resource. The groundwater level can be managed using irrigation scheduling and avoiding over irrigation in the irrigation schemes.

Introduction

Water is essential for life. The important of water can be understood from the fact that since times immemorial man has been living along rivers and water bodies and all the major civilizations flourished in river valleys. The advent of well technology around 4000 B. C. made it possible to sustain civilizations in the arid environments.

Water has always been a scarce and extremely valuable resource of the Kingdom of Saudi Arabia. The Kingdom had a humid past around 10000 to 30000 Y.B.P. The fossil water occurs as groundwater in the hydro geological provinces of the Kingdom. Out of the total available water resources 40% is used for domestic purposes, 8% for industrial and 47% for agriculture (Anon, 1992). The annual per capita water resource is 148 m^3 in Saudi Arabia. The increasing demand or water due to intensive agriculture has increased the water demand of the country to about 7.5 billion cubic meters in 2000. Surface water resource in Saudi Arabia is found predominantly in the west and southwest of the country. In 1985 (1405/06 AH), surface water provided 10% of the Kingdom's supply while 84% came from the groundwater by abstraction from the deeper aquifers, which are mostly non-renewable. Hence, regional assessment of groundwater is necessary for better management of water resources. Since the available water resources are scarce and limited in areal extent, an integrated approach is proposed for optimum utilization of the available resource.

Agricultural Development

The agricultural development had been emphasized during last two decades by strategic aspiration to attain food self-sufficiency. In Kingdom of Saudi Arabia the total cropped area is 1185000 hectares out of which the irrigated area is 420000 hectares (Sadik and Barghouti, 1994). With the adoption of modern technologies of sprinkler and drip irrigation an impetus has been provided in the agricultural development by opening the areas with low water holding capacity for cultivation.

With the increasing demand of the water by the growing population, industries and the agriculture, water management of regional aquifers has become essential. With the intent of optimal management of regional in Wadi-e-Shiran; modeling was attempted to determine the groundwater level behavior when water is abstracted for agricultural activity. A case study of A- Busayta, Al Jouf in parts of Wadi Al-Sirha, Northwestern Saudi Arabia had been presented in the present communication (Fig. 1).

The model had been developed using FEFLOW groundwater modeling software. The geology has regional control over the groundwater resources of the area. The regional stratigraphic, structural framework, landform characteristics, metrological parameters and hydro-geological milieu have been considered in determining the boundary conditions for simulation modeling (Rumikhani, 2002). The aquifers in the area are non-homogenous in behavior; in the present study two-tier aquifers model had been conceived with different hydrological properties (Fig.2). The Geometry of Al Jouf and Tabuk aquifers were obtained from the well logs, geophysical logs and the well design data obtained form the company records.

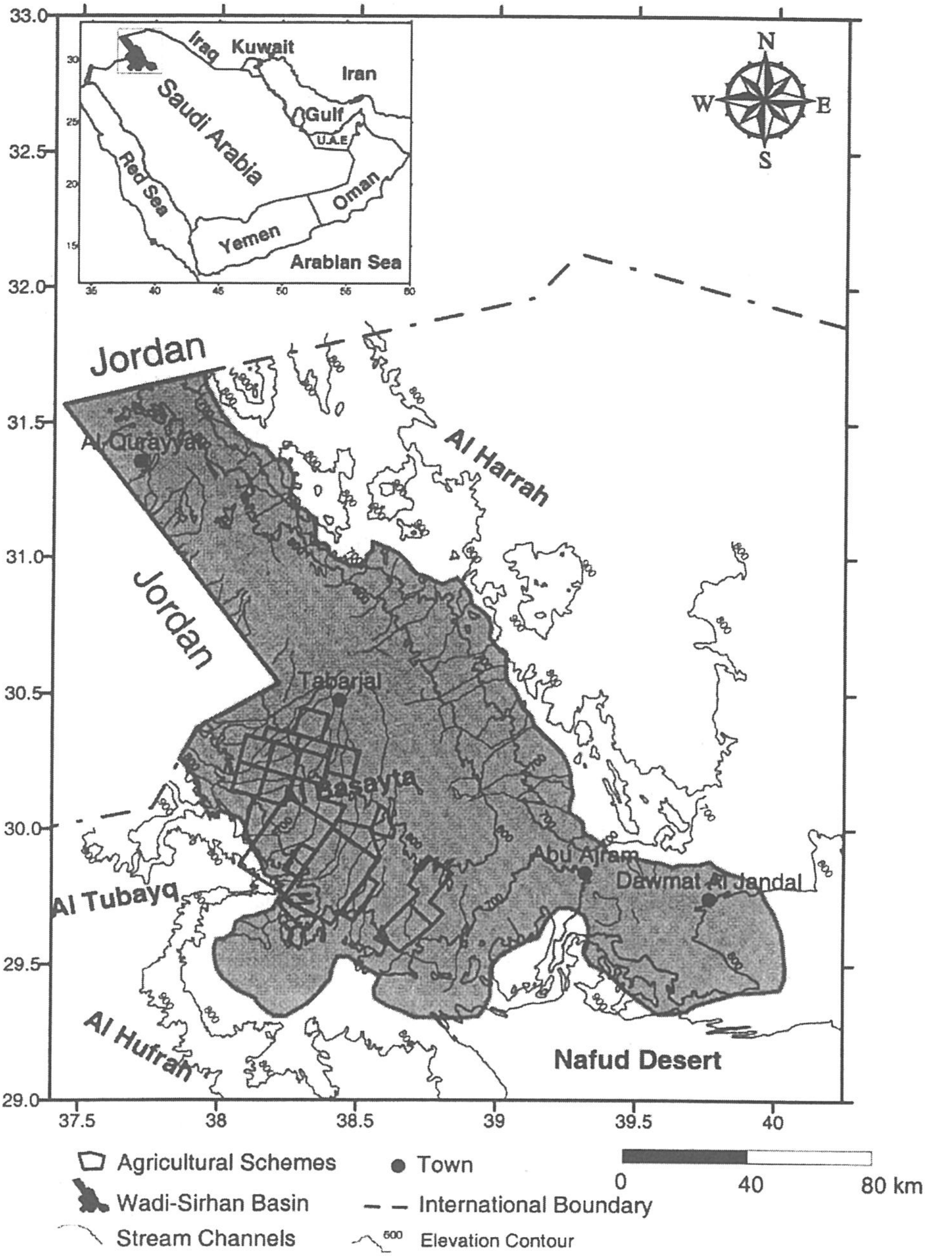

Fig. 1. Location Map of the study area

Hydrogeological setting of the area

The study area forms part of the Nafud Basin in the northern part of the kingdom. The Nafud Basin (Anon, 1984) has been separated on tectono-sedimentary considerations into three distinct hydro geological provinces namely Tabuk Basin in the west, Al-Sirhan Basin in the middle and Wadian Basin Margin in the east (Edgell, 1997). The northwest-southeast Erytgraean trend of Von Wissman controls the drainage of Wadi Al-Sirhan. The area is having high degree of structural complexity as described by Power et al., (1966); Greenwood, (1972). The Jouf area lies along the Hail Arch, which is the prominent north-south trending structural feature of the North Arabian Plate; it from part of the Interior Homocline (Edgell, 1997) and has sub-horizontal northeasterly to easterly formational dip. Stratigraphically wadi Al-Sirhan is having Palaeozoic, Mesozoic, and Cenezoic sequence resting with a first order unconformity over the Precambrian basement. The stratigraphy of the Wadi-e-Shiran in the Kingdom of Saudi Arabia is in state of flux. The regional frame work established through field surveys and exploratory drilling has established that the Precambrian crystalline's of the Arabian shield constitute the basement which is expected at >-200 m below mean sea level in the Jouf region (Tabuk); Table-I presents the generalized stratigraphic sequence of the region.

Table – I

Quaternary Group	Fine, unimodal, well sorted sand with sub angular to sub rounded quartz clasts constituting the cominant mode in the classic population. Highly porous, permeable and partly stabilized sand.
Middle Cretaceous	Wasia Formation: Sandstone interbedded with siltstone, shale and limestone, marine shoreline sediments
Early Carboniferous to Late Devonian Goundwana Super group (?)	Sakaka Formation: Non-marine Clastics, comprising sandstone interlayered with clays mainly Kaolinite layers. Coeval plant life manifested by pollens preserved in the subcrops, obtained from drill cores.
Devonian	Jouf Formation: Marine sediments comprishing limestone, fine grain sandstone with interbeds of shales towards base. Gypsum beds occur intersrratified with shale
Lower Ordovician	Tabuk Formation: Medium to fine grained sandstones alternating with shale, resting over the Proterozoic of the Arabian shield with first order unconformity
Proterozoic	Graywacke, siltstone, phylite (Riyadh – Mecca Highway at base of interior Homocline), granite, granodiorite and basic intrusives

Two-tier aquifers exist in the area supported by the Jouf Formation and Tabuk Formation of Paleozoic age (Fig.2). The wells, which are drilled beyond a depth of 400 meters, yield water form both the Jouf and the Tabuk aquifers. The groundwater condition in the area is assessed in terms of water quantity and quality. The depth to water level, discharge, recharge and flow within the aquifer has been studies to suggest a sustainable model for groundwater management in the area considering different sceneraios.

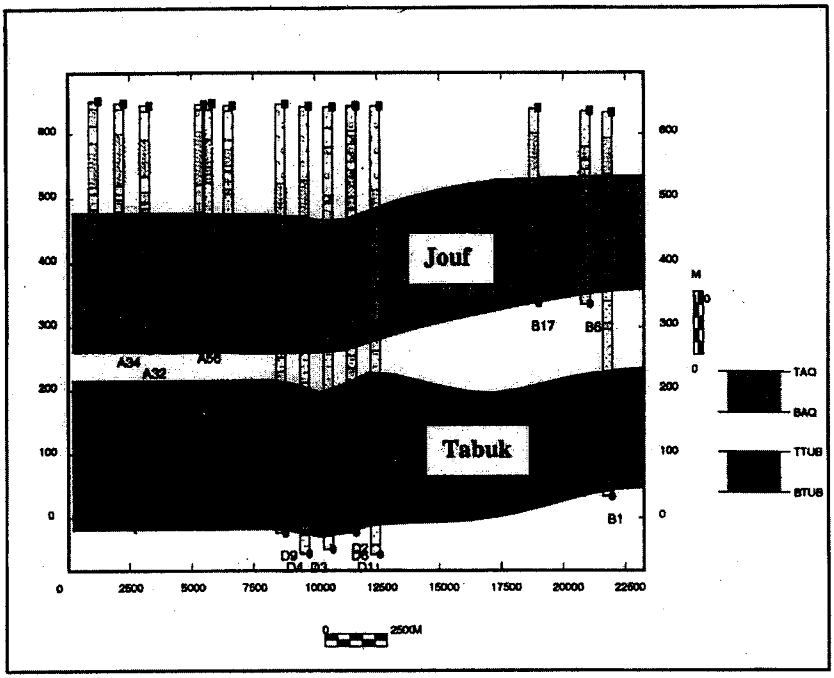

Fig. 2 Two Tier Aquifers in Parts of the Study area.

Material and Method

The model used in simulation is a finite element groundwater model FEFLOW. The following are the model descriptors:
Dimension: Three-Dimensional
Type: Saturated
Number of Layers: 2
Number of Slices: 3
Vertical Exaggeration: 1.00:1
Projection: Horizontal (Confined aquifer)
Problem Class: Separate Flow Process
Time Class: Steady Flow
Time Stepping Scheme: Fully implicit with constant time steps
Element Type: 6-noded triangular prism
Mesh Elements: 21776
Mesh Nodes: 14250
Constant recharge boundary is taken in the southwestern portion of the study area and constant head in the northeastern.
Initial heads of 1987 were taken for calibration

Specifying all these conditions creates a model. The present model is a finite element model based on localized assumptions and observations confined within the study area around the agricultural lands.

Discussion

The fixing of boundary condition is essential in groundwater modeling. In the present model we have assumed Constant recharge boundary since the available resources of the aquifer will constantly provide the water to the wells as long as it can. The study is aimed to model the aquifer behavior over the period of years, thus the model was attempted for 20 years. The natural limits of the aquifer and the geological structures and boundaries were taken into consideration while generating the model (Rumikhani, 2002). The aquifers and the associated formations are having a regional dip towards the northeast, which is the direction of groundwater flow in the aquifers. The surface topography defines a northerly dip upto south of Tabarjal and a southerly dip north of Tabarjal, thus defining a valley in which lies the city of Tabarjal, and adjoining villages. The highway to Jordan lies in the axis of the valley (Fig.1)

The groundwater model in the steady state is considered with the initial heads available from the company for 1987 and 1991 (personal communication of JADCO officials with the principal author). The maximum heads are observed in the northwest, east and southeast of the study area and lowest are found in the central, south, northeast. The trend of head show that a trough exists in the central part as the head decreases from northwest towards the central part and again increases in southeast. This variation in the hydraulic head can be attributed to high pumping in the area, since the available water level data of the area may not be truly static as there is continuous abstraction of water and the development of this – depression can also be attributed to the litho logy and stricture in the area.

The Hydrogeologic properties of the aquifers in area of study were determined using the pumping test data available at Jouf Agriculture Development Company. Data of only 30 wells was available in the company records, these wells are not well disposed and are only confined to limited zones in the southern part of the study area. The basic intent of these observations available with the company is to determine the setting depth of the well rather than determining the aquifer characteristic. During the present study no pumping test was attempted so we have used the data available with the Agricultural Company for modeling the groundwater scenario in the region.

The transmissivity varies in different parts of the aquifers depending upon their lithology. The transmissivity of Jouf aquifer ranges between 260 and 3500 square meters per day (0.003-0.04 square meters per seconds) and that of Tabuk aquifer varies between 1600 to 6400 square meters per day (0.018 to 0.074 square mters per second) (Anon, 1984; Edgell, 1997).

The hydraulic conductivity was obtained for wells by dividing the transmissivity by the aquifer thickness in each well. The hydraulic conductivity of Jouf aquifer varies from 1.6 to 27.7 meters per day (0.000019 – 0.00032 meters per seconds) and for Tabuk aquifer the hydraulic conductivity between 8.2 to 24.6 meters per day (0.000095 to 0.00028 meters per second) in parts of study area. The maximum hydraulic conductivity values are found in north; south and eastern parts of the aquifer and minimum are in central and western parts of the aquifer. Most of the aquifer is having high hydraulic conductivity, which may be attributed to the fractured lithology and caves and dissolution in limestone.
The values for storages coefficient given by Edgell (1997) were used in the present model and it is 0.02 for the unconfined part of the aquifer and 0.007 for the confined part of the aquifer.

Taking the initial heads of 1987 and calibrating them with the head of 1991 did the model calibration. The hydraulic conductivity vakues and transmissivity were varied within the specified range to make the best possible arrangement between the heads of 1987 and 1991 (Fig. 3). The 1987 and 1991 values being known the observation were biased.

The model was also calibrated by keeping transmissivity and storativity as constant and charging the draw down(q).

The calibrated model can be used for prediction using different abstraction rates, based on the total water requirements for different crops in the region. The initial condition was assumed that all the wells in the study area were pumped at a rate of 10000 m^3/day for 1825 days and on comparison of these future heads with the initial heads it was observed that there will be drop in head in the area.

Taking the present assumption of pumping 18250000 m^3 water from each well the water level showed a decline in the head, which is highest in the northern part of the study area where water-mining condition is observed.

Keeping all other assumptions same only selective pumping was attempted and five wells namely W12, W14, W70, W81 and W83 were pumped for 7300days, since in these parts the drawdown is minimum.

The steady state calibration process involves adjustment of hydraulic conductivity in the aquifer. To refine the model further the hydraulic heads distribution of 1991 was taken as initial head and the model was calibrated, similar observations were made as were for 1987.

The hydraulic conductivity distribution and simulated heads were used for steady calibration. The hydraulic conductivity values were available for eight location; the attempt was made to change its values at two locations to observe the change in the hydraulic head.

Since the main criteria for steady state condition was the hydraulic heads and there should be a good agreement between the observed and the simulated heads, it was achieved and the model can now be subjected to a transient state calibration using storages coefficient as a controlling factor.

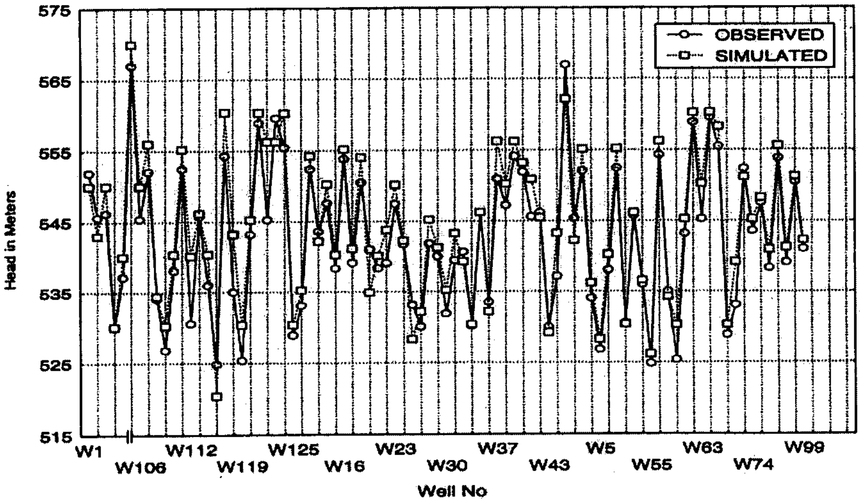

Fig. 3. Observed and Simulated heads after calibration

Scenarios

Different scenarios have been hypothecated for predicting the long term behavior of aquifers. The crop water requirement of crops had been taken into consideration for calculation to total desired abstraction from well. The total crop water requirement (TCWR) depends on numerous factors and is expressed as:

(TCWR) = Etc/Ea x (1+LR)

Where
Etc is crop water requirement in mm/day
Ea is Application Efficiency in percent
LR is leaching Requirement in mm/day
The crop water requirement (Etc) is defined by relation

Etc = ETo x Kc

Where
ETo is evaporation in mm/day
Kc is crop coefficient

The leaching requirement is quite variable and vary for different type of soils, it can be expressed by relation:

LR = ECw/(2MaxECe) x 1/LE

Where
ECw is Electrical Conductivity of well in mmhos/cm
ECe is Electrical Conductivity of soil in mmhos/cm
LE is Leaching efficiency in mm/day
Based on these calculations the Total crop water requirement was estimated for Alfalfa, Wheat, Potato, Tomato Crops in Wadi Al-Sirhan area (Table-2)

Table – 2

S.No.	Crop	Season	Total Crop Water Requirement in m^3/ha/season
1	Alfalfa	January – December	34059.00
2	Potato	January – April	8254.00
3	Potato	October – January	6042.00
4	Wheat	November- February	4310.00
5	Wheat	January – April	7250.00
6	Tomato	October – January	5378.00
7	Tomato	February – May	11514.00

The total cropped area in the Wadi Al-Sirhan has been calculated using remotely sensed data through techniques of digital image processing. The total areas of all the Center Pivots in the year 2001 was 104814.88 ha (Rumikhani, 2002)
For visualization of the groundwater behavior different scenarios were considered by assigning different crop to the center pivot as seen in the classified remotely sensed image and to calculate the total crop water requirement.

The total crop water requirement for Alfaalfa for season extending from January to December is 34059 m^3/ha, thus for the total water requirement for 1573 center pivots 78611.16 ha in Wadi Al-Sirhan is 2700 million m^3 and the effect of this crop is shown Fig.4

The total crop water requirement for Potato for season starting from January to April is 8254 m^3/ha. For cultivation of potato in this season in the total cropped area of 5240.744 ha the water requirement is 34 million m^3 (Fig. 5)

The total crop water requirement for wheat grown in season starting from January to April is 7250 m^3/ha, thus for the cultivated area of 4192.59 ha, the total water requirement is 27.14 million m^3 (Fig.6)

The total crop water requirement for tomato in season starting form February to May is 11514 m^3/ha. The crop covers an area of 3144.4464 ha, which requires 26.086 million m^3 of water (Fig.7).

The Total water requirement of the area is approximately 2787.226 million m^3 and the effect of this withdrawal is shown in Fig.8.

Conclusion

The final step in modeling is to predict the behavior and response of the aquifer using different discharge rates. Our first alternative was to assess the change in water level if all the wells in the study area are pumped at the rate of 10000 m^3/day for five years resulting in drop in future heads of the study area. When the simulated head is compared with initial head it shows that there is a constant change in water levels after five years in most of the study area, except in the northern part of the study area where is maximum Drawdown observed is 24.57 meters which us very harmful for the aquifer and it is not advisable to pump water in the that area. Keeping in mind the result of first alternative, in the second alternative, only selected wells were chosen for pumping the water (W81, W83, W70, W43 and W12). The criteria behind choosing these wells were the resultant Drawdown of first alternative, because drawdown is minimum in these areas. In our second alternative the said wells were pumped for 20 years at the rate of 10000m^3/day, suggesting detrimental effect on the aquifer.

It is recommended that optimal use of groundwater may be done for environmentally compatible and ecologically sustainable agriculture. The crop water requirement is to be calculated and as per the requirement the irrigation may be done. The condition of the wells is to be assessed so that in the areas where the water mining condition is existing those wells may not be pumped constantly. The tanks may be constructed which may hold water from remote wells and can supply it to the center pivots, which need more water.

The wells in the area are having high discharge rates. In Jouf Aquifer the well discharge vary from 1500 gpm to 2500 gpm and in Tabuk Aquifer it is over 2500 gpm. This suggest that the wells in Jouf Aquifer have an abstraction rate of 8208 m^3/day to 13680m^3/day and in Tabuk the abstraction is more than 14000 m^3/day.

The daily crop water requirement for each crop should be calculated for each growth stage and the irrigation schedule shall be prepared to avoid over irrigation and minimize the use of precious resource.

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1. Alawi, Al Jamil and Abdulrazzak, Mohammed, 1994. Water in the Arabian Peninsula – Problems and Perspectives. In Water in the Arab World Perspectives and Prognoses, Ed. Peter Rogers and Peter Lydon, Harward University Press, pp. 171-202.

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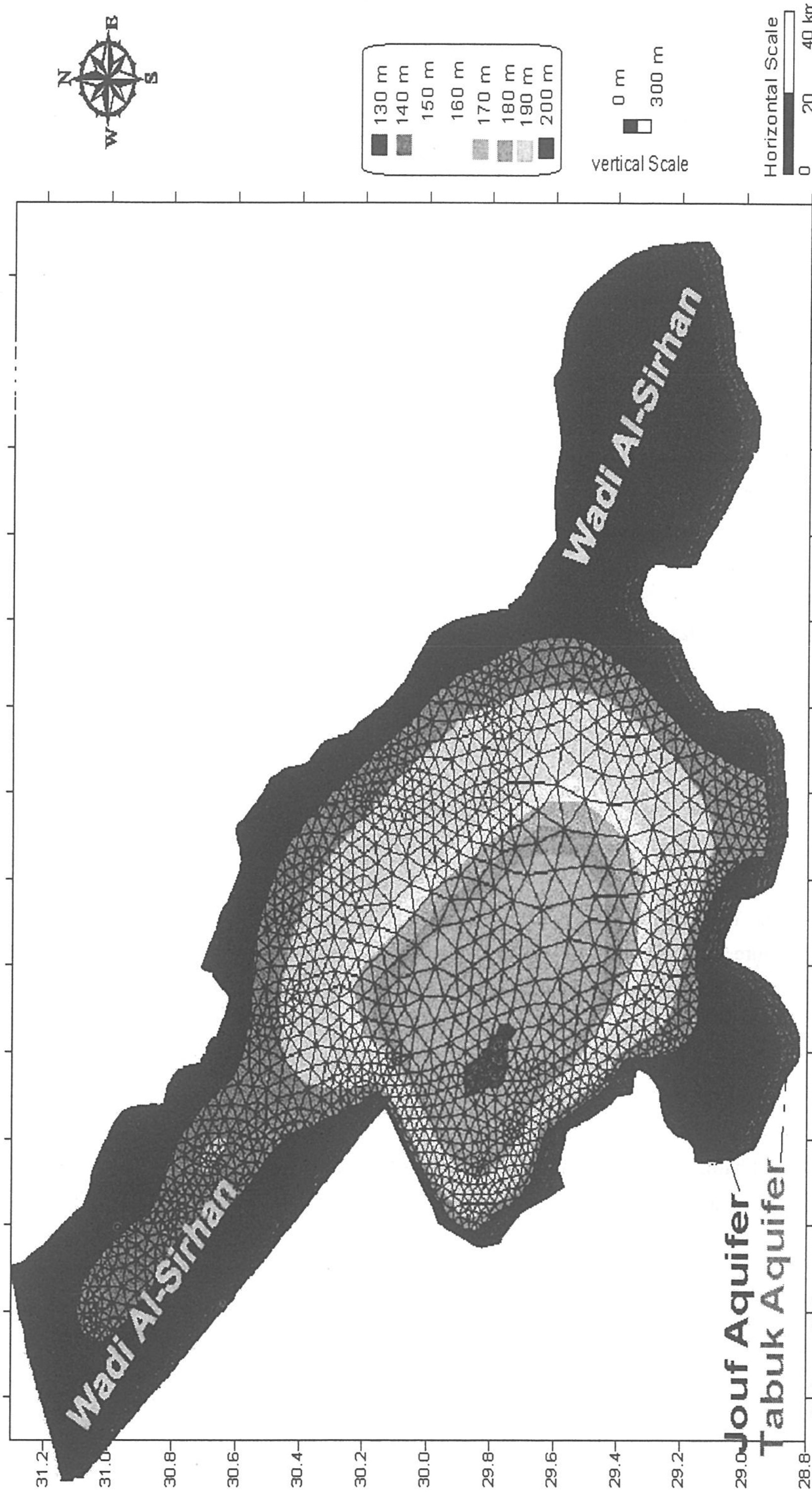

Fig. 4. Simulated heads for alfalfa, year 2001

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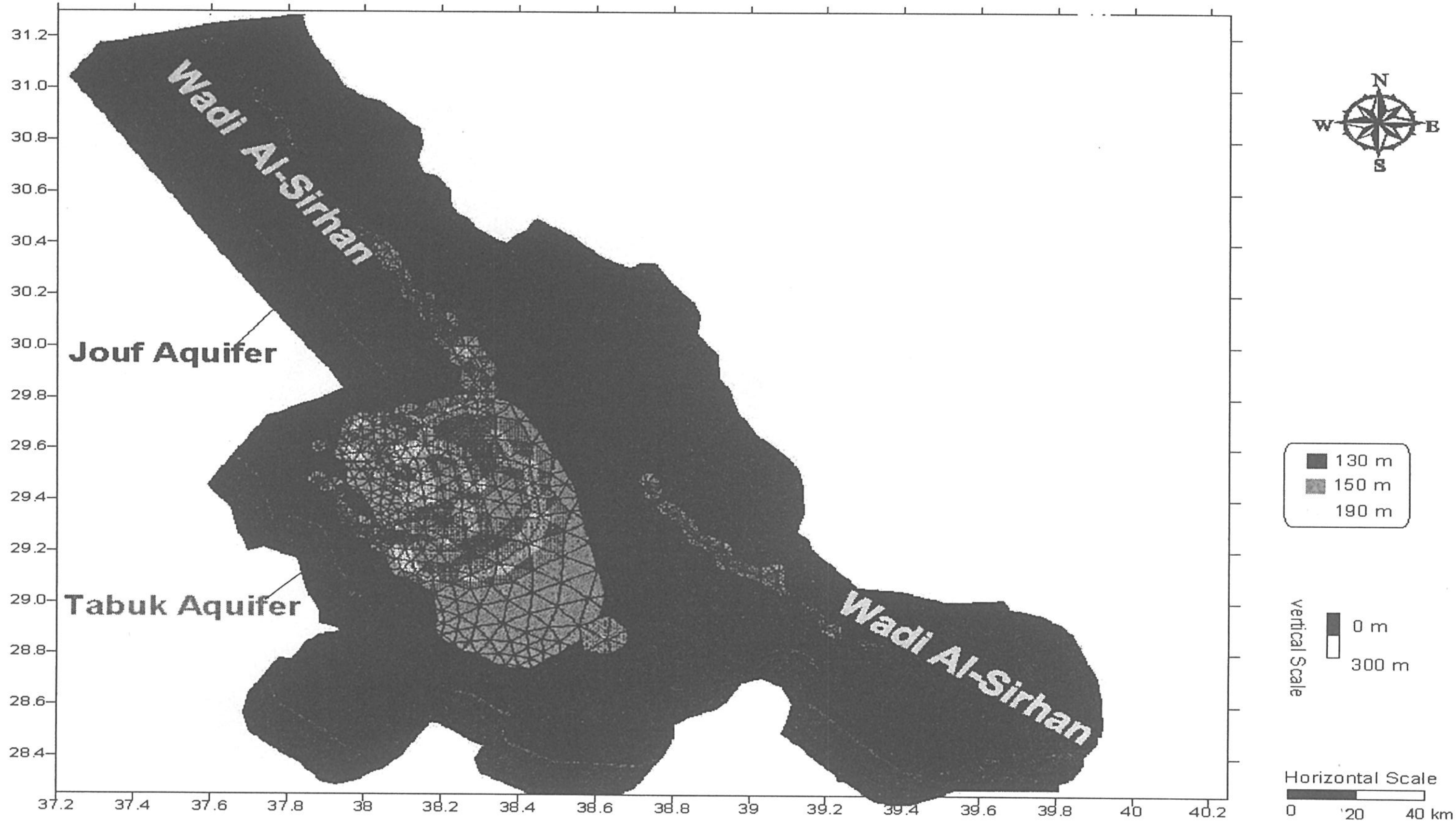

Fig. 5. Simulated heads for Potato year 2001

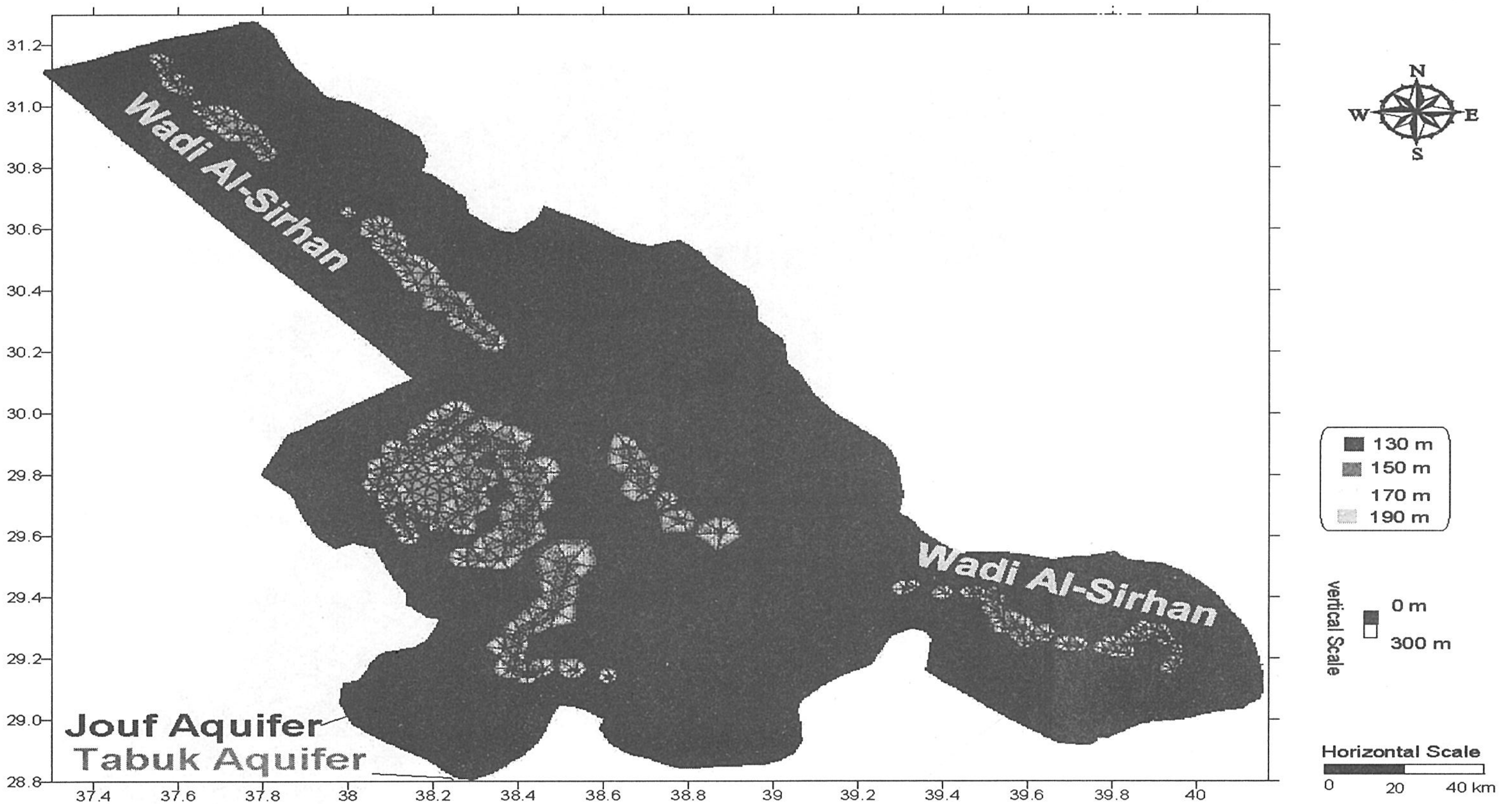

Fig. 6. Simulated heads for Wheat, year 2001

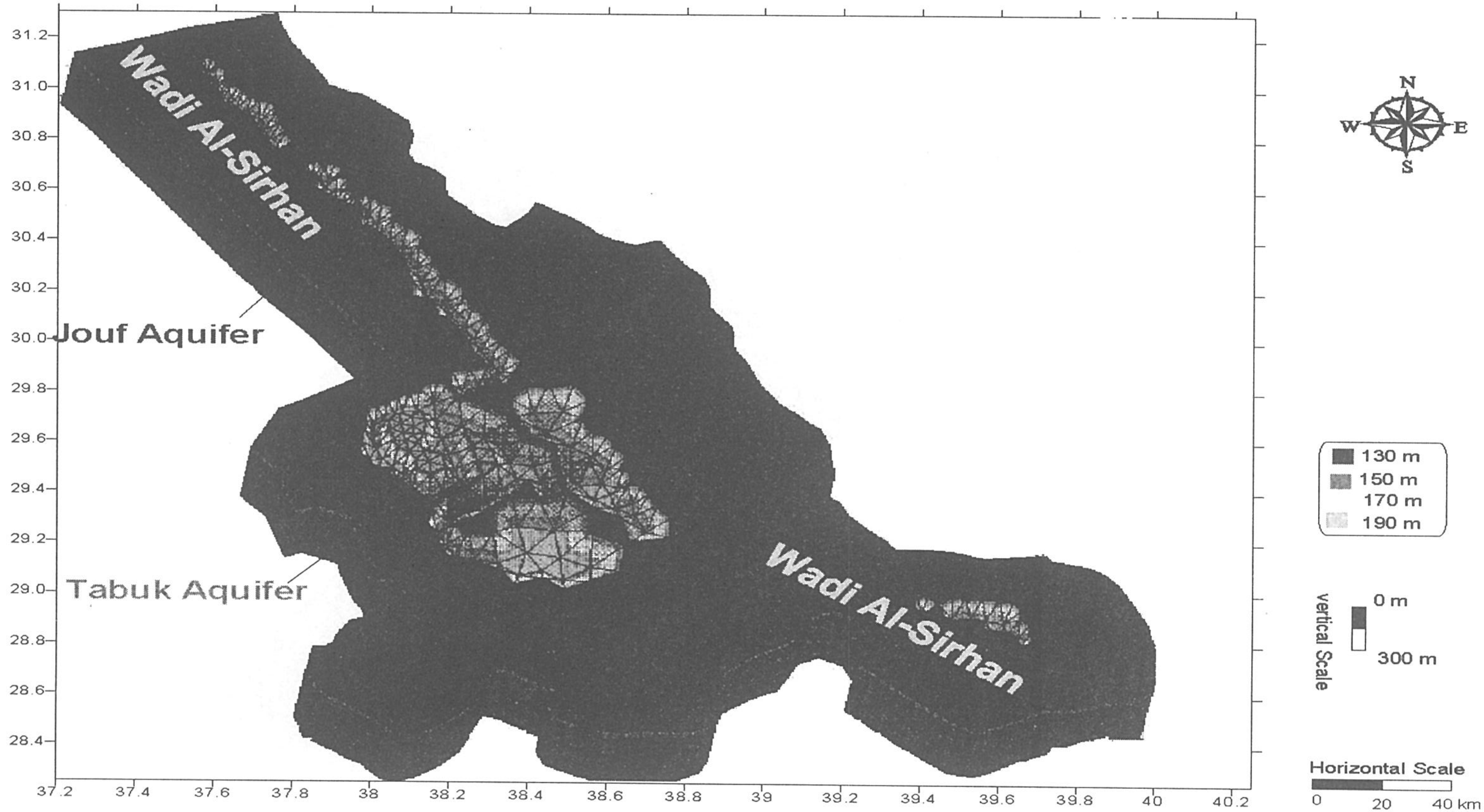

Fig. 7. Simulated heads for Tomato, year 2001

Solid Wastes Storage in unlined Landfills at Yanbu (Saudi Arabia)- Contamination of ground water resources

Dr. Joseph Sebastian Paimpillil, Munir Dehlawi and Leo Dennis (India)

Solid wastes Storage in unlined Landfills at Yanbu (Saudi Arabia) - Contamination of ground water resources.

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Royal Commission for Jubail & Yanbu (RC) has developed and implemented a comprehensive environmental control policy to protect public health and the environment of Madinat Yanbu Al-Sinaiyah (MYAS). Waste materials are monitored from source of generation to ultimate disposal to avoid adverse environmental effects. The industrial wastes landfilled in RC landfills varied between 46000 to 74000 tons during 1995-2000. Groundwater monitoring requires testing of groundwater qualities to determine whether waste materials have escaped from the landfill.The distribution of salinity and pH in landfill area had similar patterns. The region under the influence of leakage from the oil drum storage area and area S_1had higher pH than in the south east corner. The salt content in the ground water had low value in the boreholes of landfill area S_1. (<13%). A low salinity ground water movement out of area S_1, carrying high oil content from area S_1 and from the drum storage area resulted in the oil contamination of the ground water. The salinity around landfill area S_3 (SE corner) was nearly ten times higher than of the area S_1. The low salinity tongue originating from area S_1 indicated the direction of ground water flow. The low yearly mean salinity in the ground water had coincided with the region of high groundwater oil content. The yearly averaged minimum salinity (49.11%) in the groundwater was at the bore hole closest to the drum storage area. The region surrounding waste storage area S_3 had very high yearly average salinity (>100%) and very low oil content (<0.4mg/l) . The landfarming of crude oil tank sludge at the northern corner seemed to be associated with the high oil contents (>5.1mg/l). The ground water in the waste disposal area S_1 was slightly contaminated by oil with the maximum (4.3mg/l). The influence of landfill area and the waste disposal site on oil contamination of ground water seemed to be diminishing in the southerly direction. The region north of waste disposal site S_2 seemed to be out of danger from oil contamination of ground water. A southwesterly movement of oil contaminated ground water in the RC waste disposal site can also be inferred from the distribution pattern of oil content in the ground water. It could be said affirmatively that waste disposal in RC landfill area is contaminating groundwater aquifer and the waste disposal in un-lined cells for weathering and the storage of oil drums remained as a potential source of ground water contamination.

Keywords: unlined landfills, oil contamination, ground water

Introduction

In ground water resource evaluation, the quality of ground water is of nearly equal importance to quantity. The ground water quality data give important indications of ground water recharge, discharge, movement and storage. The groundwater table may be only a foot below the ground's surface or it may be hundreds of feet down. The water table may rise or fall depending on many factors. For many years, ground water was thought to be protected from contamination by the layers of rock and soil that act as filters, but contaminants do make their way into the ground water and affect its quality. Most of the contaminants that commonly cause concern originate above the ground, often as the result of human activities. In areas where material above the aquifer is permeable, pollutants can sink into the groundwater. Groundwater can be polluted by landfills, septic tanks, and leaky underground gas tanks. Although source reduction, reuse, recycling, and composting can divert large portions of municipal solid waste (MSW) from disposal, some waste still must be placed in landfills. Once ground water is contaminated, it is usually very difficult and costly to clean. A study of the differences and changes in chemical composition of ground water may be useful in determining the source or sources of recharge and direction of flow. Modern landfills are well-engineered facilities that are located, designed, operated, monitored, closed, cared for after closure and cleaned up when necessary. Landfills have a protective bottom layer to prevent contaminants from getting into the groundwater. However, if there is no layer or it is cracked, contaminants from the landfill can make their way down into the groundwater. After an aquifer has been contaminated it is difficult to entirely define or isolate a contaminant plume. It is also difficult and extremely costly to remove it. Even after the source of contamination has been removed, an aquifer may remain contaminated for anywhere from a few years to a few centuries.

Madinat Yanbu Al-Sinaiyah (MYAS) is one of the largest industrial complexes in the Middle East. The heavy industries operating in the city are petroleum refineries, crude oil terminals, petrochemical complexes, titanium dioxide plant, and infrastructure facilities, among others. The light and supporting industries either depend on the heavy industries for raw materials or support them with supplies and services. Royal Commission has developed and implemented a comprehensive environmental control policy to protect public health and the environment of the region. Accordingly, waste materials are monitored from source of generation to ultimate disposal to avoid adverse environmental effects. Wastes generated in MYAS are grouped into two main categories: solid, or non-hazardous wastes; and hazardous wastes. Non hazardous wastes are grouped into four categories: domestic, commercial, and institutional wastes; industrial wastes; sewage sludge and special wastes. Non hazardous solid waste is disposed at the municipality- owned and operated sanitary landfill. All ponds, pits, or trenches dug for solid waste disposal were excavated not more than 0.7meters from ground level or within 0.5 meters above the ground water level, which ever is less. The vulnerability potential of an aquifer to groundwater contamination is in large part a function of the susceptibility of its recharge area to infiltration. Areas that are replenished at a high rate are generally more vulnerable to pollution than those replenished at a slower rate. Unconfined aquifers that do not have a cover of dense material are susceptible to contamination. Groundwater monitoring requires testing of groundwater wells to determine whether waste materials have escaped from the landfill.

Methods and Materials
Land Fills In MYAS

The RC landfill is a disposal facility where hazardous wastes are placed in or on land. The waste constituents, their characteristics, and the methods, which were used to treat the wastes, play a major role in deciding the type of landfills in which they are finally disposed of. Two type hazardous waste landfills are employed in MYAS. The Class-I (or double lined) landfill with leak detection and leachate collection and removal systems and the class-II (or single lined) landfill with leachate collection and removal system. The single lined (class II) landfill is used for the disposal of treated inorganic waste materials. Other hazardous wastes such as residue of incineration, inorganic waste with high level of heavy metals, waste contaminated with toxic organic compounds, and certain organic wastes, which can not be incinerated, are disposed of in class I landfill after proper treatment. The Royal Commission sanitary landfill is located in the southeastern portion of its property in area covering land blocks C-4 and C-5 (Fig.1). The RC landfill has been receiving different types of hazardous and semi-hazardous industrial waste materials from MYAS industries since 1985.

Hazardous Industrial Waste Area (Site-I):

This site measures 640mx170 m (108800 square meters). At this site, different types of industrial semi-hazardous wastes such as spent FCC catalyst, molecular sieves, spent alumina, spent Fullers earth, spent clay and wax materials have are into unlined landfill cells. Contaminated hazardous wastes like oil contaminated FCC catalyst, fuel oil tank sludge, calcium fluoride sludge, pyrophoric scales, leaded and unleaded oily sludge materials have either been land treated or stored. Various types of waste oil from different sources were discharged for six years into waste oil holding pond. Discharge of waste oil into holding pond was stopped since 1995.

Semi-hazardous Waste Area (Site-II):

This area measures 850m x 300m and is located in the southern corner of block C-5 in sanitary landfill. Presently, wastewater treatment plant sludge from Cristal facility, spent clay and wax materials from Best Foods, Calcium Fluoride sludge from Samref are disposed/ stored/ weathered at this site in unlined cells. The by-product sulfur from Luberef is stored in HDPE lined cells. The waste heavy fuel oil and diesel from Power Plant were stored in concrete lined pond of 17x12x1.5 m pond on temporary basis.

Saudi Aramco Land-farm Site (Site-III):

This site measuring 300m x 300m is located at the northern corner of land block C-4 outside of landfill. This site was specifically allocated to Saudi Aramco for land farming of crude oil tank sludge generated from cleaning of crude oil storage tanks.

Drummed Waste Storage Area (Site-IV):

An open area was allocated at the domestic waste landfilled area A1 near area 5_1 in block C-4 for storing hazardous waste materials in drums. This site is divided into 5 cells with specific names according to type of wastes stored. These are the flammable (ignitable) waste cell, Acidic waste cell, Caustic waste cell, Organic/ miscellaneous waste cell and Spent catalyst (contaminated) cell. Hazardous wastes such as spent CHD catalyst, NHT catalyst, Co/Mo catalyst, used batteries, paint waste, miscellaneous chemicals, waste oil, fuel oil sludge, battery electrolyte solutions, lube additives, among others are being temporarily stored at this site until an ultimate hazardous waste disposal facility starts operating in MYAS.

Groundwater Sampling And Analysis.

RC has installed 27 boreholes in and around the RC landfill site (Fig 1) as detailed in the environmental monitoring plan GST 4035 (Anon.1985). The ground water samples were collected from boreholes by means of a specially designed pump and analyzed for oil contamination .The water level in the wells, temperature and pH were measured in situ.

Results and Discussion.

Soil overlying the water table provides the primary protection against groundwater pollution. Some chemicals are absorbed or react chemically with various soil constituents, thereby preventing or slowing the migration of these pollutants into the groundwater. Just as any man-made filtering device can be overloaded, so can the natural filtering capacity of soil. Large amounts of potential pollutants concentrated in a small area can cause localized groundwater contamination, depending on the depth, type of soil above the water table and quantity and quality of wastes.

The RC Power Plant had generated and stored about 60 tons of off-spec fuel oil. The Cristal industrial facility had generated and disposed approximately 51708 tons of the WWTP sludge at RC landfills in the current year, which is more than 90% of total waste generated from MYAS. The PD &SC facility had stored a total of 711 drums of hazardous wastes. This facility also discharged about 168 tons of off-spec fuel in concrete lined pond in the landfill area. The SAMREF facility had disposed 176.75 tons of Calcium Fluoride sludge at a designated area at RC landfill by weathering method. The Luberef -II had disposed 30.36 tons of sulfur in the landfill area. The IBN_RUSHD – Polyester Plant facility had stored 465 drums of ethylene glycol residue and 92 drums of bio-sludge at the drum storage area. The FUCHS petroleum facility had stored 380 drums of hazardous wastes. The BEST FOODS, during the first six months of the year 1998, had disposed about 140 tons of spent clay and 141 tons of spent wax at the designated site in the Landfill area. The composition and types of wastes generated and disposed at the RC landfills are given in Table (1) and the quantity of oily wastes generated at different RC facilities is shown in Fig (2).

Most of the wastes are currently being land disposed or temporarily stored at the RC landfill. During the current year about 51708 tons of industrial waste materials were land filled. All of this waste (except 0.23 tons of expired medicines) was wastewater sludge from CRISTAL facility. Further, some 1311 drums containing hazardous wastes were also stored at the drum storage site of the landfill. Also about 181 tons of waste oil was discharged in to the concrete lined pond at the landfill area. The amount of industrial wastes handled at the RC landfill facility during 1985-1999 period are shown in Fig.3

Groundwater Quality

The yearly averaged values for groundwater characteristics (water level, temperature, salinity, chlorinity, pH and oil and grease) are given in the table 2. The yearly ranges for various parameters remained as (10.0 - 30 C) for temperature, (3.9-12.30m) for water level, (5.0-8.5m) for pH, (8.9-181.4 %) for salinity, (4448-100468 mg/l) for Chlorinity and (0.40 -7.10 mg/l) for oil. The overall mean values for the RC landfill area was 19.38 C for temperature, 7.26m for water depth, 7.25 for pH, 77.93% for salinity, 42333.74 for chlorinity and 1.31mg/l for oil.

Water Levels

The water table is the surface on which the fluid pressure of the ground water is equal to atmospheric pressure. Its depth at any point can be determined by observing the water level in a shallow well open to the atmosphere. The water table represents the height to which the basin bas been saturated with water in aquifer, and changes in the water level in wells that tap the basin are direct indications of the change in the volume of water in storage. From water level elevations, the direction of ground water flow, the influence of recharge, effluent seepage, seawater intrusion etc. can be identified. The yearly averaged water levels at the boreholes of the RC landfill area fluctuated between 5.67-9.7m. The water level in the vicinity of landfill area 5 (2) was less than 7m. and were out of danger from leakage from the waste farming sites. The annual mean water level is shown in Fig.4a. Many groundwater bodies often get mixed with saline water due to low groundwater flow rate, high tides and lowering of water table due to excess withdrawal of ground water. If water table falls below the mean sea level, negative gradient sets in allowing seawater to flow into the aquifer. High saline water intrusion was found in majority of wells surrounding area 5(2).

The yearly averaged pH of the ground water varied between 6.78 and 7.8. The lowest pH (6.78) was recorded in area 5(1). The general pattern of salinity Fig(4c)and pH distribution Fig (4b) in RC landfill area had similar patterns. The observed maximum levels of pH in the ground water had a narrow range (7.0- 7.9) for the RC landfill area. The region under the influence of leakage from the drum storage area, landfarm and area 5(1) had higher pH than the area to the vicinity to the area 5(2).

Salinity distribution

The one-year ground water quality data showed high levels of salinity and chloride in ground water. The salt content in the ground water had shown very low salinity (Fig 4c) in the boreholes of landfill area 1. (<13%). The groundwater in borehole BH4 & BH9 also had low salinity. These points towards a low salinity ground water movement out of area 1, carrying high oil content from area 1 and from the drum storage area and resulting in the oil contamination in the ground water of the boreholes BH4, BH10 and BH 9. The salinity values observed in the region around landfill area 5 had nearly ten times higher salinity than of the area 1. The low salinity tongue originating from area 1 indicated the direction of ground water flow in the RC region. The low yearly mean salinity in the ground water of the region had coincided with the region of high groundwater oil content. The yearly averaged minimum salinity (49.11%) in the groundwater was observed at BH4, which is the closest bore hole to the drum storage area. The next lowest average salinity (56.8%) was noticed at borehole BH9 and this well was also associated with the high oil content. The distribution of salinity minimum is shown in Fig (4c). The boreholes with low salinity are in the proximity to landfarm site. The region surrounding waste storage area 3 had very high yearly average salinity (>100%) and very low oil content (<0.4mg/l) in the ground water.

Oil Contamination

The distribution of oil in the groundwater of the RC landfill area is shown in Fig (4e,d). The landfarming of crude oil tank sludge by Saudi Aramco at the northern corner of land block C(4) seemed to be associated with the high oil contents at BH13 (5.1mg/l) and at BH22 (5.6mg/l). The high oil content in groundwater of boreholes BH9 (7.1mg/l) and BH10 (5.5mg/l) seemed to be the result of various types of waste oil from different sources discharges into the holding ponds of the industrial waste area (Site 1) up to 1995. The oil contamination in the vicinity of site 1 was intensified by the disposal of fuel oil tanks sludge, leaded and unleaded oily sludge material and oil contaminated FCC catalyst. The boreholes 1-

3 are situated in the industrial waste disposal area 1 and the ground water in the boreholes of this region was slightly contaminated by oil with a maximum of 4.3mg/l at BH1. Though BH5 is very close to the industrial waste-dumping site, the oil content in the ground water was below the detection limit of the equipment. Just inside the landfarm site, the groundwater was moderately contaminated with oil at BH 7 (2.4mg/l). Just outside the southern boundary of landfill , the contamination of groundwater was high with value upto 7.1mg/l at BH9. The influence of landfill area and the waste disposal site on oil contamination of ground water seemed to be diminishing in the southerly direction and reached to low values of 0.4mg/l at BH12. The region north of waste disposal site 5(2) seemed to be out of danger from oil contamination of ground water. An indication of the southwesterly movement of oil contaminated ground water in the RC waste disposal site can be inferred from the distribution pattern of oil content in the ground water.

Clustering of Boreholes

A cluster analysis using five ground water quality variables had identified three distinct cluster formations (Fig 5a) of the boreholes. The hierarchical tree formation Fig(5a) shows the major clustering of boreholes. Three major clusters are visible in the tree formation. The cluster A (Fig. 5b) included the boreholes having high oil content and low salinity for the ground water. This cluster clearly indicates the source of oil contamination in the ground water as the drum storage area, the landfarm site and the landfill area 5 (1). The low salinity tongue (Fig 4d) observed in cluster A region could indicate the direction of movement of the oil-contaminated ground water. The cluster B includes the boreholes with moderate oil contamination from the landfills. These wells seemed to be under the combined influence of the leaching from land area 5 (1 &2). The cluster C includes all the other boreholes of the region, which were practically untouched by the wastes dumping in the landfill. The groundwater in this region had very high salinity and very low amount of oil contamination (<0.04 mg/l).

Conclusion

Over the past one-year period, oil and grease exceeded the minimum detection limit of 0.4ppm of the equipment. It could be said affirmatively that waste disposal in RC landfill area is contaminating groundwater and the waste disposal in un-lined cells along with storage of oil drums remained a potential source of contamination. Although, discharge of waste oil into ponds was stopped in 1995, the pond was not cleared of the waste oil and remains as a potential source of contamination of ground water. Based on the ground water monitoring studies, the following recommendations are indicated. Dumping of waste oils in un-lined pond should be stopped at the earliest feasible. Controlled lined pond should be constructed, if required, for storing waste oils. Measures should be taken to recover oil and dispose properly the contaminated soil from the existing pond area. Disposal of industrial wastes in un-lined ponds shall be discouraged. Impact from disposed waste shall be evaluated, and if warranted, necessary measures should be implemented to minimize adverse environmental impacts. Most significant characteristic of ground water quality deterioration is the fact that it is usually a cumulative process. It is easier to prevent than to purify, once pollutant concentrations have reached problem proportions.

Acknowledgment

The authors are grateful to Saudi Binladin (O&M), Jeddah for allowing to use the data collected for the Environmental-Monitoring Project GST 4035 awarded to them by Royal Commission for Jubail and Yanbu.

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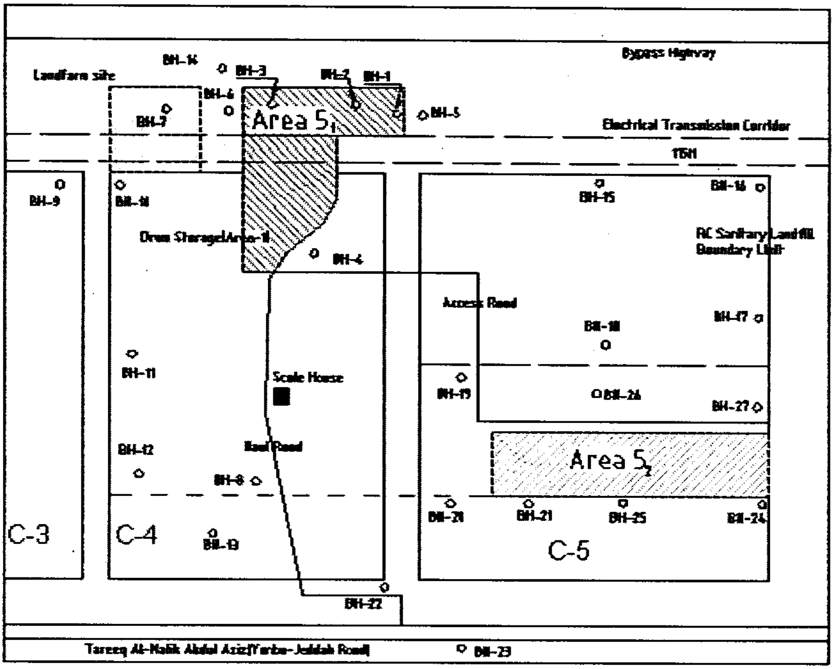
Anonymous (2000), Annual Report of Environmental Monitoring Project, GST 4035, M/S



Saudi Binladin (O&M), Jeddah, pp 250.

Figure 1. Location of Boreholes , Landfarm and Drum storage locations in RC area.

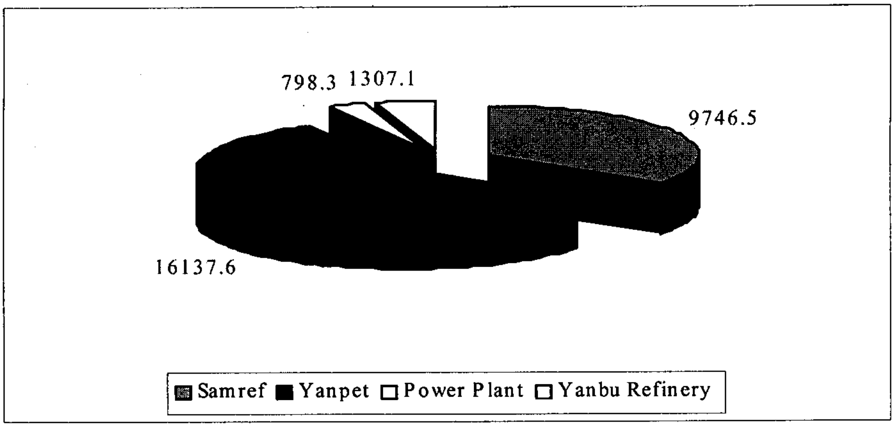


Figure 2. Oily wastes in (tons) handled from major facilities at RC landfill.

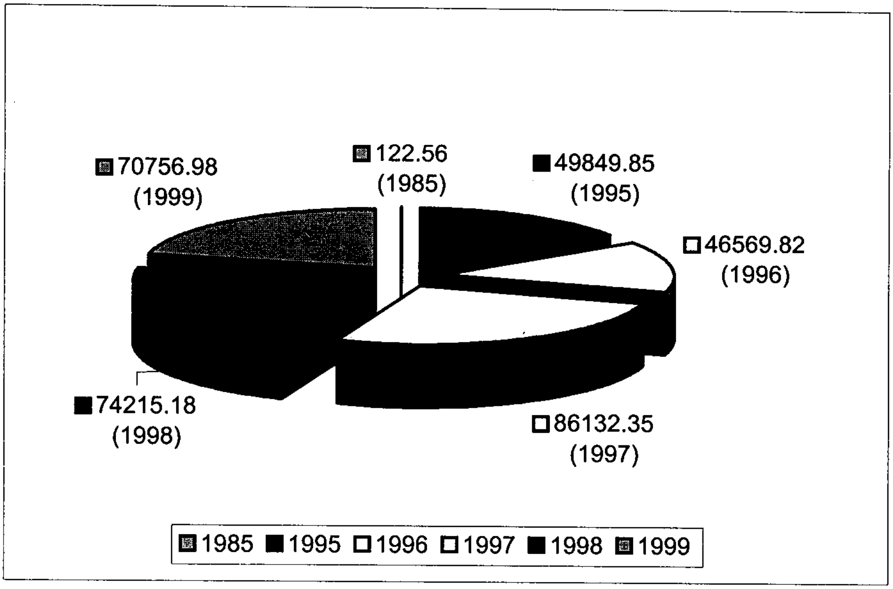


Figure 3. Amounts of industrial wastes (tons) at RC landfill during 1985-1999.

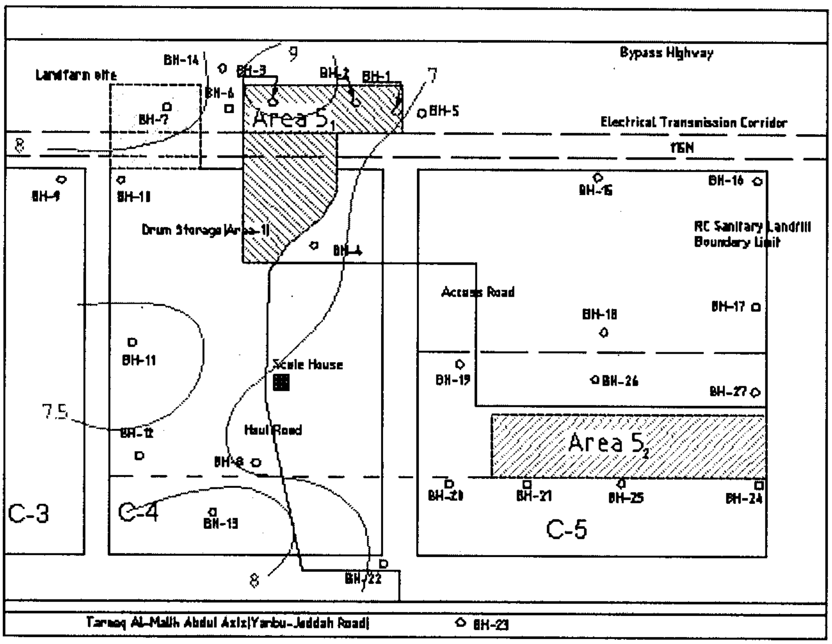


Figure 4a. Annual mean water levels (m) in boreholes

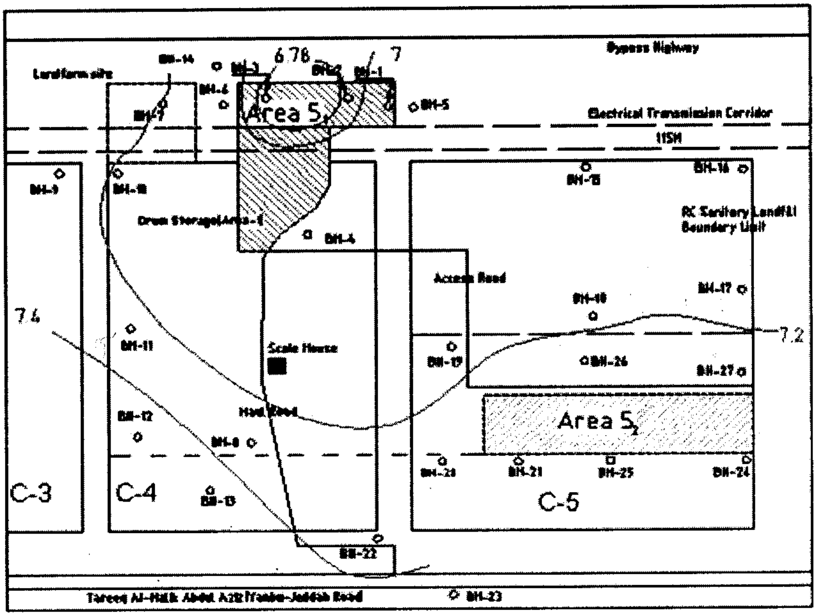


Figure 4b. Mean observed pH in the ground water of RC area.

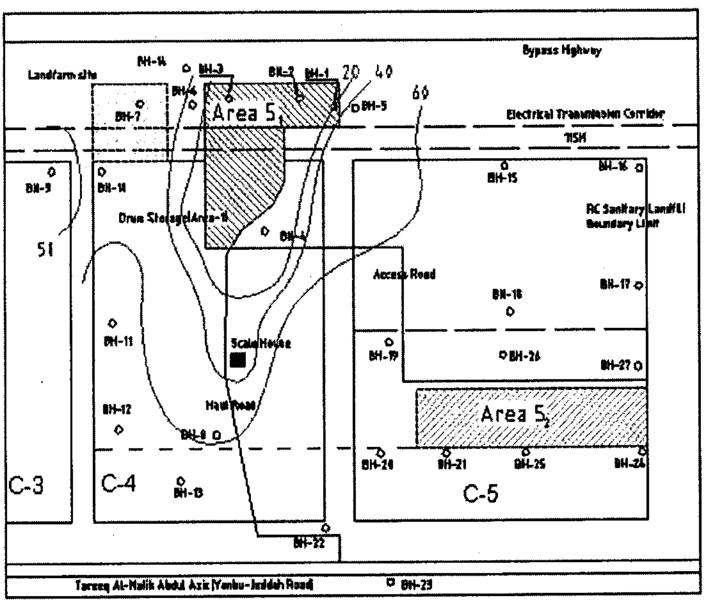


Figure 4c. Distribution of Salinity minimum (ppb) in RC landfill area.

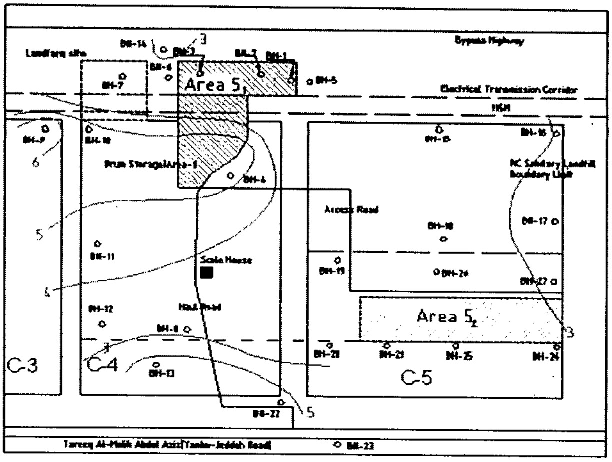


Figure 4d. Distribution yearly mean oil contents (mg/l) in boreholes.

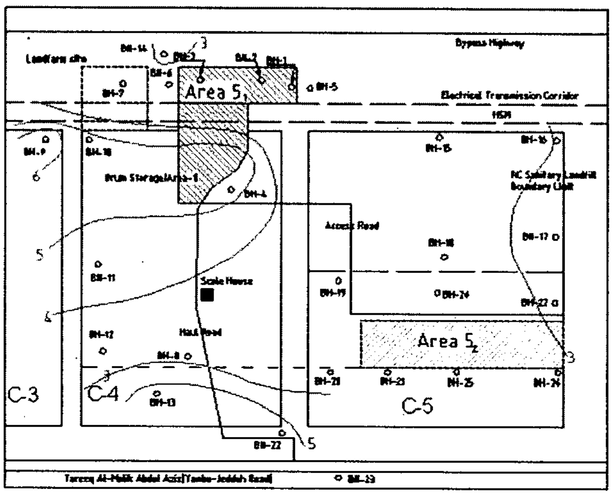


Figure 4e. Distribution of maximum oil contents (mg/l) in RC boreholes.

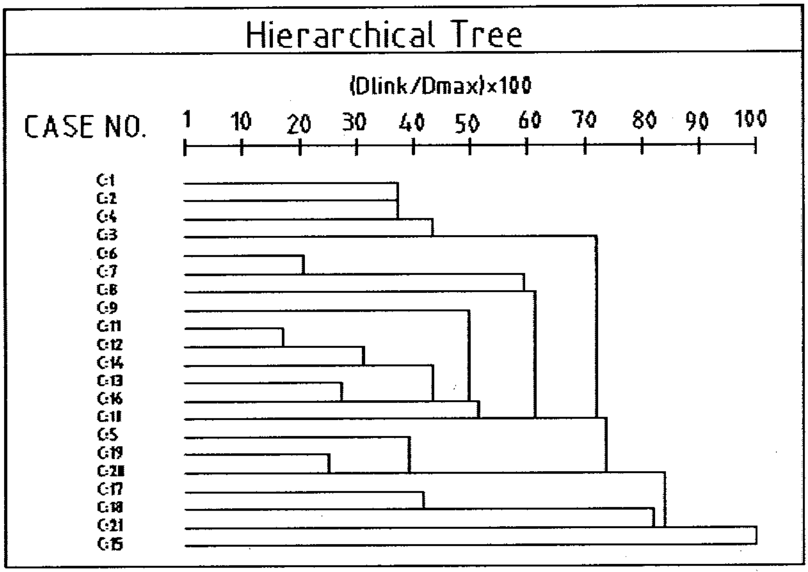


Figure 5a. Clustering of Boreholes in RC region

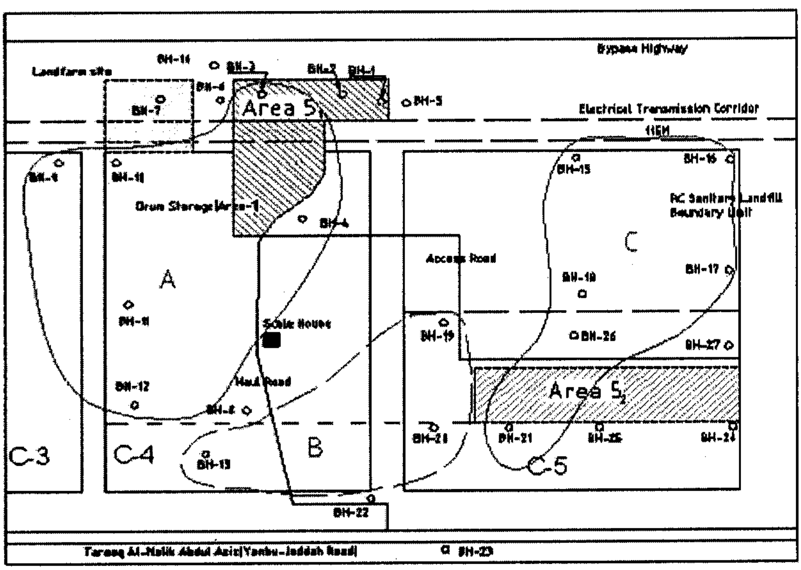


Figure 5b. Three cluster groups of Boreholes in RC landfill area.

Table.1 Composition and types of wastes generated and disposed at RC landfill.

Waste name	Generated by	Quantity	Disposal method	Disposal facility
Effluent waste oil	FUCHS	66 drums	Drum storage	RC landfill
Off-spec lube oil	FUCHS	25 drums	Drum storage	RC landfill
Spent grease	FUCHS	39 drums	Drum storage	RC landfill
Used lube oil	FUCHS	250 drums	Drum storage	RC landfill
Total for FUCHS		380 drums	Drum storage	
STG soot	PD&SC	711 drums	Drum storage	RC landfill
Waste heavy fuel oil	PD&SC	168.14 tons	Oil pond	RC landfill
Total for PD&SC		711 drums 168.14 tons	Drum storage Oil pond	
Curing agent	RC-MHD	1 drum	Drum storage	RC landfill
Paint material	RC-MHD	46 drums	Drum storage	RC landfill
Silicon sealant	RC-MHD	1 drums	Drum storage	RC landfill
Waste engine oil	RC-MHD	13.2 tons	Oil pond	RC landfill
Total for RC-MHD		48 drums 13.2 tons	Drum storage Oil pond	
Used oil	SALACO	172 drums	Drum storage	RC landfill
Wastewater sludge	CRISTAL	51708.1 tons	Land filling	RC landfill
Expired medicines	RC-MC	0.23 tons	Land filling	RC landfill
Spent NHT catalyst	Yanbu Ref.	18 tons	Land filling	SEW AlKhobar
Rust scales	Yanbu Ref.	10 tons	Land filling	SEW AlKhobar
Total for Yanbu Ref.		28 tons		
Spent FCC catalyst	SAMREF	536.5 tons	Feed for cement	EP cement co.

Oily sludge	SAMREF	3070.91 tons	Land farming	SEW AlKhobar
Charcoal	SAMREF	24.34 tons	Land filling	NEPC BeeA'h
Contaminated sulfur	SAMREF	98.16 tons	Land filling	SEW AlKhobar
Jet Merox salt	SAMREF	83.28 tons	Land filling	SEW AlKhobar
MTBE catalyst	SAMREF	95.39 tons	Land filling	SEW AlKhobar
Spent alumina	SAMREF	98.32 tons	Land filling	NEPC BeeA'h
Spent clay	SAMREF	297.05 tons	Land filling	SEW AlKhobar
CaF2 sludge	SAMREF	176.75 tons	Weathering	RC landfill
Total for SAMREF		4480.7 tons		

Table 2. The annual means of groundwater characteristics.

Borehole	Temperature C	Depth (M)	pH	Salinity (ppb)	Chlorinity (mg/l)	Oil (mg/l)
1	18.31	8.31	7.32	56.89	29591.77	1.10
2	17.38	7.91	6.78	57.82	31994.63	0.61
3	17.86	5.38	6.97	72.99	36882.00	0.82
4	18.60	7.19	7.16	49.11	23190.20	1.08
5	19.00	6.27	7.07	112.93	62500.67	0.40
6	19.00	8.31	7.07	72.47	40143.43	0.96
7	19.75	8.45	7.30	78.83	43713.50	0.90
8	22.00	6.63	7.30	96.31	49347.00	0.55
9	19.71	6.97	7.34	56.81	31464.57	2.28
10	19.71	7.76	7.19	63.12	35009.14	2.28
11	19.60	7.54	7.32	73.18	40532.40	1.28
12	22.33	7.43	7.40	71.43	39563.33	0.40
13	21.50	8.73	7.45	90.31	50018.17	2.00
14	19.00	6.12	7.17	62.70	34721.03	1.98
15	20.33	6.65	6.93	110.70	61319.33	0.40
16	18.50	6.30	6.80	136.05	75359.00	1.70
17	19.00	6.75	7.05	136.30	75531.00	1.85
18	15.67	5.67	7.27	143.13	79475.00	0.65
22	21.29	6.90	7.81	84.80	46964.00	1.44
24	16.00	6.75	7.30	94.80	52536.00	0.40
26	23.00	5.25	7.35	109.75	60793.00	0.40
27	17.33	5.53	7.20	165.37	90886.33	1.33

Palestine Water Resources Management Strategy

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Palestine Water Resources Management Strategy

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Abstract

Palestine is experiencing a severe water crisis caused mainly by the lack of control over the Palestinian Water Resources. At present the average per capita water consumption by the Palestinian population is approximately 55 l/c/d, or 55 % of the WHO Minimum Standard of 100 l/c/d. The above statements show that the communal water supply for the Palestinian population is substantially inadequate by international standards. The available water resources in the Middle East are scarce, limited, fragile and threatened. They are already exploited, especially in Palestine. The water resources in the countries of the sub region (the Jordan River Basin) are limited in absolute terms. A large proportion of the water resources in the middle east in general, and in Palestine as particular, are transboundary and final arrangements on water resources allocation between Palestinians and Israelis are not yet in place for "fair and equitable apportionment". The Middle East region's natural water is not only threatened, it is also threatening(1). The resource management strategy in the West Bank is defined by the word sustainable. In general, sustainable management of a resource provides for long-term exploitation of the resource up to or below a level at which adverse conditions may occur. West Bank water sector stakeholders have explicitly stated their goal of achieving sustainable management of water resources. This goal is a key principle of the West Bank water resources management strategy and has implications toward management actions that must be taken in the development of the West Bank water sector. Specifically, aquifer sustainable yields must be well understood and aquifer management plans defining specific well abstraction scenarios must be developed and followed. In addition, water quality must be protected to ensure a sustainable resource.

Keywords: Water Resources, Supply, Demand, management, Consumption

Water Resources in Palestine

It is important to understand that, as a basis of discussion, the water resources available in the region are limited in scope and time. The chief surface water resources in the region are the Jordan River drainage basin. Its headwaters are located in the northern Israel and the Israeli occupied Golan Heights and Southern Lebanon, which feed Lake Tiberias. The lower Jordan River is fed from springs and runoff from the West Bank, Syria and Jordanian water (mostly in Yarmouk River). As a whole, these elements constitute the Jordan international drainage basin, a naturally defined area that cannot be artificially sub-sectioned. Palestine has been denied any of the Jordan River's Water, although it is full riparian.
The Johnson Plan, for the Middle East water allocation, while officially not ratified by all the parties but generally adhered to propose a West Ghur Canal to provide the West Bank with 120 MCM to meet the needs of the Palestinians. Unfortunately, this plan never saw the light.

Groundwater

Groundwater is the main source of water in Palestine. The West Bank Aquifer System, which has three major drainage basins:
The Western Basin, which, while supplied and recharged from the West Bank mountains, located within the boundaries of the West Bank and Israel.
The Northeastern Basin, which is located inside the West Bank near Nablus and Jenin, and drains into the Eocene and Cenomanian-Turonian Aquifer under the north of the West Bank.
The Eastern Basin, which is located within the West Bank and the springs from which represent 90 percent of spring discharge in this area.

It is worth noting that while this aquifer system discharges approximately 600-660 MCM annually, West Bank Palestinians exploit currently a mere 115-123 MCM, the other amount is exploit by the Israelis. The existing situation and the present water crisis is not chiefly one of insufficient supply, but of unquotable and uneven distribution.

The Gaza Strip Aquifer, while its part of the coastal aquifer, has been continuously over pumped for quite some time in large part to serve the high population. In addition, Israel has been tapping this aquifer and its replenishment from outside Gaza Strip. Most of water resources experts agreed upon the sever crisis of the water situation in Gaza Strip. The water table has been pumped to far below the recharge rate, and there is evidence of deteriorated water quality of the aquifer.

Israel presently controls the major part of water resources, the Jordan River Basin and West Bank Aquifers. As a result of Israel's occupation of the Golan Heights and its control over southern Lebanon, Israel controls the headwaters of the Jordan River. Through the occupation of the West Bank, and the restrictions on Palestinians access to their water resources, Israel controls both the westward-flowing aquifers and all waters flow eastward into the Jordan River. Furthermore, Palestinians are prevented from fully utilizing the West Bank's underground water resources. During the Israeli occupation period, permission for well drilling must be obtained from the military authorities. Permits had been granted for only 23 wells. Rigorous water quotas are imposed on Palestinians. Supply is often restricted leaving communities without water for considerable periods, and excess pumping is punished by heavy fines. (2)

An interim allocation of water rights has been agreed upon between Palestinian Liberation Organization (PLO) and Israel in Oslo 2 Interim Agreement in 1995. This allocation basically maintains the status quo, thus manifesting the principle of prior appropriation, but allows for an additional development of so far unexploited resources by the Palestinians of 23.6 MCM in the West Bank plus an additional 5 MCM to be supplied to Gaza via Israeli system until the year 2000. Furthermore the agreement states that the total additional needs of the Palestinians might rise to 70-80 MCM after the year 2000.

The abstraction of the so far unexploited resources mainly refers to the eastern aquifer, which is considered not transboundary, which is difficult to access, and which water resources are not clearly known in terms of quantity and quality.

As mentioned earlier, the final allocation of water rights between Israelis and Palestinians, both on the Jordan River and on the mountain aquifer, is still pending. Thus the final availability of water resources in the West Bank in terms of water ownership rights is still open. (3)

Whatever the final status agreement will proclaim, resources will be limited, even with minimal growth scenarios. A German-sponsored (GTZ) long-term water supply and demand study for the Jordan River riparian, Jordan, Israel and Palestine predicts regional water gaps by years 2000, 2010, and 2040. In three growth scenarios, ranging from a minimum of about 600 MCM per year by 2000 to a maximum of 3.4 BCM per year by 2040.
According to the study, total average demand by the year 2040 for the West Bank and Gaza Strip, would amount to about 1.1 BCM per year (767 MCM for the West Bank, 319 MCM for Gaza Strip), leaving a shortfall, as compared to Oslo 2, of 800 MCM per year. (4)

Table 1
Groundwater resources in Palestine

No.	Basin.	Israeli Cons.	Palest. Cons. From wells.	Palest. Cons. From springs.	Quantities available for development.	Total estimated yield of the aquifers.
1.	Western	340	20	2	-	362
2.	North Eastern	103	25	17	-	145
3.	Eastern	40	24	30	78	172
4.	Gaza Aquifer					55
	Total	483	69	49	78	734

* Data in the table is taken from article 40 of Oslo B agreement. (5)
* Cons.: consumption.
* All quantities in MCM/yr

The water level in the aquifers varies among the different places. In Jenin sub-series, water can be found at 50 meters below the ground surface, while in other formations it is generally deeper. In Jerusalem and Bethlehem, the water level varies between 130-160m below the ground surface, while in Hebron, Upper and Lower Beit Kahil formations, it can reach 200-300m below the ground surface. Such depth is generally a factor of the depth of the overlying strata.

Springs

There are 297 springs in the West Bank, 114 out of which are considered to be the main ones with substantial yield quantities. Usually there are fluctuations in the yield of some of these springs in the different years, depending on the rainfall quantities, and thus the recharge to groundwater. However, their average annual yield is estimated to be around 60.8 MCM/yr. Most of the water quantities from springs are used for irrigation, while only around 1.6 MCM/yr are used for domestic consumption at the time being. Unfortunately, information about the use of each of these springs (domestic or agricultural) is not available, but it is true for many of them that their water is used for the two purposes. (6)

Surface Water

Compared to groundwater, surface water is considered to be of minor importance in the West Bank. There is only one river which the West Bank has access to that is Jordan River. There are also four permanent wadis in the area, while the rest are seasonal ones. In addition to that, there is some other surface water bodies like the seasonal lakes of Marj Sanur.

Jordan River

It is the only river which the West Bank has access to. At the time being, however, the West Bank uses nothing of its water. According to the Johnson plan of 1955 the share of Jordan (together with the West Bank) was estimated to be 774 MCM/yr out of 1287 MCM/yr, the total quota for all riparian countries of the river. Out of the 774 MCM/yr share of Jordan, the West Bank share is found to be around 215 MCM/yr.(7)

Wadis and Seasonal Lakes

Mostly the Wadis are of seasonal type as they flow only in the winter season during the flood periods, which happen just few days every year. There are quite many wadis in the West Bank, some of which flow to the west reaching towards the Mediterranean Sea, while the others flow to the east until they reach the Jordan River. Only four wadis are permanent in the West Bank, all of which flow to the east and reach the River Jordan. These are: Wadi Fara'a, Qilt, Malih and Auja.
The quantities of lost flooded surface water are estimated to be 70 MCM/yr. (8)

In addition to these wadis, there are seasonal lakes in the West Bank, especially Marj Sanur in Jenin Governorate. It floods and becomes full with water in the winter season. It remains full for several months of the year, depending mainly on the rainfall quantities and distribution. This "lake" can provide the West Bank with additional millions of cubic meters of water annually.

In general, surface water bodies, whether wadis or seasonal lakes, are not studied well yet. There is a need for more detailed and extensive studies in order to have better estimates for the available water quantities in them, and to find out the best ways for using their water.

Non-Conventional Water Resources

Cisterns

Among the other resources, cisterns are of major importance in the West Bank Governorates. They are widely distributed throughout the area, even though the attention paid to them is different from one place to another in the West Bank. The water quantities in the cisterns are used mainly for domestic purposes. The typical form of these cisterns is to collect water from the roofs of the buildings in the winter season, and store it in an underground hole in most of the cases. The dimensions of these cisterns are usually different, but mostly have volume ranging between 60-100 cubic meters.

Cisterns act as a major source of domestic water supply in the localities that do not have water supply networks. It is estimated that 6.6 MCM is utilized from the cisterns. In localities where water networks exist, cisterns still act as another "good" source of domestic water supply. (9)

Wastewater Re-Use

The reuse of wastewater has been thoroughly investigated in many studies performed for the water sector in Palestine. The main issues concerning the reuse of wastewater, such as collection system, treatment plants, regulations, standards and guidelines, are not available.

Brackish Water Desalination

It is a known fact the Gaza aquifer and some potential sources from the eastern aquifer in the West Bank suffer from a high salinity rate. It is estimated that 53 MCM/year of brackish water in the West Bank from al-Fashkah springs, and most of the Gaza aquifer needs to be desalinated. (8)

Table 2
Water balance in Palestine

Hydrologic Parameter	West Bank Contribution to Water Balance		Gaza Strip Contribution to water Balance		Total
	Percentage	MCM/yr.	Percentage	MCM/yr.	MCM/yr.
Annual Rainfall	100	2248	100	101	2349
Evapotranspiration	-68	-1529	-52.5	-53	-1582
Surface Runoff	-3.2	-71	-1.98	-2	-72
Natural Recharge	28.8	648	45.5	46	694
Return Flow		RFWB	8.9	9	9+RFWB
Overall Balance		648+RFWB		55	703+RFWB

Source: PWA. (10)

Water Supply

Around 88% residing in 345 localities in the West Bank have piped water supply systems, while 12% inhabitants residing in 282 localities do not have this service. In terms of localities (i.e. towns and villages), 55% of the localities in the West Bank have piped water supply systems and 45% are without this service.

Water Demand

The total water use by Municipal and Industrial sectors in Palestine during the year 1999 was estimated to be 101 MCM. An amount of 52MCM was used in the West Bank, whereas a total of approximately 49 MCM was used in Gaza Strip. The water consumed by the agricultural sector is estimated to be 172 MCM. (12)

Population Projection

The assessment of future population has been carried out using the PCBS census results as abase for the end of the year 1997. (13)

Table 3
Population projection

Year	Population 1000s				
	Gaza		West Bank		Total
	Urban	Rural	Urban	Rural	
1997(Census)	947.809	53.76	848.5	751.6	2601.7
2000	1108.2	102.5	1108.7	1001.3	3321
2005	1316	121.7	1285.3	1160.8	3884
2010	1525	144.5	1454.2	1313.3	4437
2020	2049	194	1861	1681	5680

Future Municipal and Industrial water Demand

The demand projections are estimated based on WHO minimum and average domestic water consumption standards of 100 l/c/day and 150 l/c/day. Our estimates distinguish between the consumption of people living in urban areas and people living in rural areas. Based on these target consumption rates and an estimated overall loss rate ranging from 40% to 25% by the year 2020, Table 6 shows the estimated municipal and industrial water demand. A demand of 432 MCM/year is projected for the year 2020 gives a total municipal and industrial annual per capita water consumption of 76 m3/year. According to quoted numbers from Israeli publications, the total annual municipal and industrial annual per capita water consumption in Israel is 150 m3/year of which is around 105 m3/year for domestic purposes.
If the projections of Palestinians demand are based on equal municipal and industrial Israeli per capita water consumption, then the total municipal and industrial Palestinian water demand will be 852 MCM/year for the year 2020. (14)

Table 4
Projected municipal and industrial water demand in mcm/year

Year	2000	2005	2010	2020
West Bank	141	179	205	262
Gaza	85	109	127	170
Total Palestine	226	288	332	432

Projection of Agriculture Water Demand

From different studies and reports, it was estimated that the agriculture water demand for the years 2000, 2005, 2010 and 2020 are about 224 MCM, 266 MCM, 299 MCM and 353 MCM, respectively. (12)

Future Potential Water Demand

The overall objective of any integrated water resources management plan is to satisfy the needs for sustainable development. To achieve this and based on the previous demand estimates, the Palestinian water sector should achieve an amount of around 785 MCM/year by the year 2020. This amount is about three times the available supply at present, but at the same time not higher than the Palestinian water rights from the renewable water resources.

Table 5
Projected total water demand in mcm/year

Year	2000		2005		2010		2020	
	M&I	Agric.	M&I	Agric.	M&I	Agric.	M&I	Agric.
Sector Demand	226	224	288	266	332	299	432	353
Total Demand	450		554		631		785	

M&I: Municipal and Industrial
Agric.: Agriculture

Water Resources Management Strategy

Water resources management strategy identified from the goals, objectives, standards, policies and priorities (GOSPPs) of the Palestinian water sector. In addition, the range of water supply and demand management solutions is described and analyzed.

GOSPP Driven Strategic Principles

The goals, objectives, standards, policies, and priorities identified and clarified by the stakeholders during integrated water resources management planning provide elements of a water management strategy in the Palestine. These principles and their implications toward water management action are described briefly below.

Resource Management

Conservation

In the West Bank considerable volumes of water are presently being lost through physical inefficiencies in the water infrastructure. Reduction of these physical losses is an important strategic principle to be achieved through implementation of conservation programs. A target reduction of physical losses to 20 percent of the gross water supply has been established by key stakeholders. This implies water management actions which include improved metering, leak detection, and network rehabilitation. The West Bank water management strategy recognizes that in this water-scarce environment, physical inefficiencies must be addressed through far-reaching conservation programs to maximize the net benefit of limited water resources.

Water Supply

Scarcity of water resources is perhaps the greatest problem facing the West Bank water sector. The West Bank water management strategy is quite clear in stating that supply should be provided to meet demand. As there is presently a gap between supply and demand in the West Bank, this strategic principle also implies action to either enhance supply and/or reduce demand. The strategy is not explicit with regard to how the gap between supply and demand should be filled. This allows for variability and flexibility in the management approaches considered by the West Bank Integrated Water Resources Management Plan (IWRMP, CH2MHILL, 2002). Supply actions such as internal resource development and importation of external resources can be considered along with demand management actions. These axes of supply development and demand management are discussed below.

Distribution

The strategy for water distribution is to improve accessibility to piped water for domestic users. A target of providing piped water to 100 percent of domestic users has been established

- Internal resources development – This axis emphasizes the development of water resources internal to the West Bank (groundwater, surface water, wastewater) to fill the water gap.
- External resources development – This axis emphasizes the development of water resources external to the West Bank (desalinated sea water or imported freshwater) to fill the water gap.
- Demand management – This axis emphasizes the reduction of demand (agricultural, municipal and industrial) to fill the water gap.

Any one of these approaches taken to the extreme may yield a potential solution for the management of West Bank supply and demand. These solutions each have consequences and risks in relation to the political complexity of implementation, potential for public acceptance, socio-economic and environmental consequences, technical feasibility, and potential costs. In addition to these extreme approaches to filling the water gap, there are an infinite number of solutions that combine these basic strategies, and thus lie between the three axes.

This "surface" of potential solutions is shown on Figure 1. The points of intersection between the surface of solutions and the axes of development were used as the basis for developing water management scenarios to be analysed with the goal of finding a preferred management solution that draws from all three axes. Each of the axes of water resources development is described in further detail below.

Internal Resources

The internal resources axis of development focuses exclusively on the use of water resources internal to the West Bank to fill the gap between supply and demand. Internal resources within or adjacent to the West Bank boundaries include:

- Groundwater that can be developed from wells
- Surface water captured from ephemeral wadi flow
- Jordan River
- Harvested rainwater
- Fresh and brackish springs
- Wastewater resources

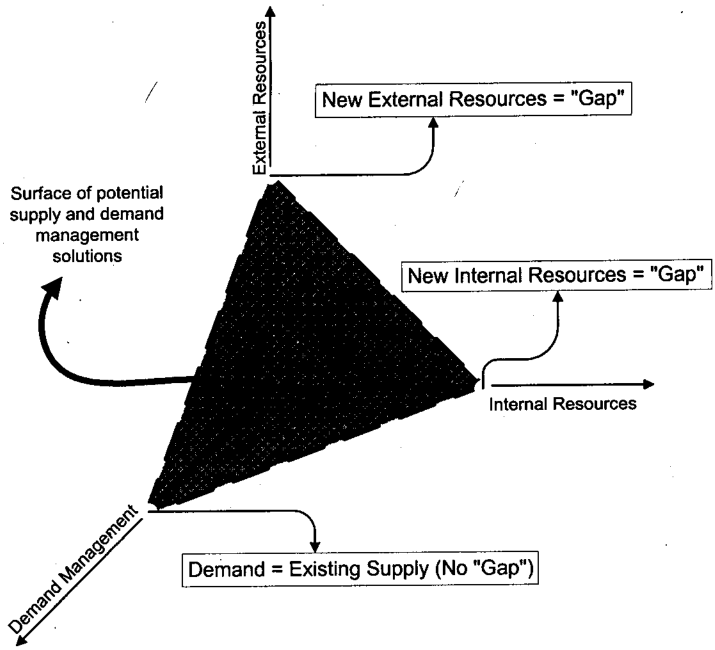

Figure 1 Potential Solutions for the Management of Water Supply and Demand

The volumetric limits to which these resources can be developed is discussed in detail in the IWRMP; however, in general, a development scenario emphasizing the use of internal resources to fill the gap between supply and demand would rely on significant additional groundwater development and access to Jordan River resources. Because groundwater resources are currently developed (by both Palestinians and Israelis) to near the sustainable limits and the lower Jordan River does not presently contain significant resources of good quality, implementation of an internal resources management plan to fill the gap between supply and demand relies on successful negotiation of Palestinian water rights to additional quantities in the Eastern, Northeastern, and Western groundwater basins and in the Jordan River. Additional supply quantities are available from wadi flow, rainwater harvesting, wastewater reuse and brackish water; however, the total volume of these resources which can be developed is not sufficient to meet the projected demand. Possible advantages and disadvantages of the internal resources axis of development are summarized below.

Table 6
Advantages and disadvantages of the internal resources axis of supply development

Advantages	Disadvantages
Security of water supply	Reliance on water rights negotiation
High technical feasibility	Limited volumes available
Autonomous management	Time required to implement may be great
Assertion of water rights	Finite limit to supply

External Resources

The external resources axis of development focuses on the use of water resources external to the West Bank to fill the gap between supply and demand. External resources may include:

- Desalinated Mediterranean Sea water (imported by pipeline)
- Desalinated Red Sea water (imported by pipeline or canal)
- Fresh water imported by pipeline
- Fresh water imported by tanker

A major advantage of the external resources axis of development is that the volumes available through implementation of external resource development options are generally large. Costs associated with specific importation options may be high. However, a scenario emphasizing external resources as the primary supply for filling the gap between supply and demand can significantly reduce the gap between supply and demand.

It should be noted that as with the internal resources option, considerable political effort must be exerted to successfully develop resources along the external resource axis. Agreements for purchase of water may be necessary and right-of-ways for conveyance to the West Bank must be attained. Firm agreements with the supplying desalination plant or freshwater source provider must also be carefully negotiated to ensure reliability of the resource.

Possible advantages and disadvantages of the external resources axis of development are summarized below.

Table 7

Advantages and disadvantages of the external resources axis of supply development

Advantages	Disadvantages
Large volumes available	High cost of water
High quality source	Political complexity of necessary agreements
Not dependent on water rights	Technically complex (desalination)

Demand Management

The demand management axis of development focuses on reduction of projected West Bank water demand to reduce the gap between supply and demand. Demand management options may include:

- Restrictions on agricultural growth
- Restrictions on domestic demand
- Implementation of water-efficient cropping patterns
- Implementation of water-efficient consumer use fixtures

Demand management emphasizes efficiency in water use and restriction of demand across the water sector over the development of additional supplies to meet projected demand. Generally, demand management schemes focus on reduction of demand in the agricultural sub-sector through sector growth restrictions and/or regulated water efficient cropping patterns to allow for growth of the municipal demand with minimal new supply requirements. This appears to be a likely scenario for demand management in the West Bank where agricultural demand is presently approximately 70 percent of the total demand and domestic water consumption is well below regional averages. Other methods to manage demand and reduce the water gap may include delaying achievement of target domestic demands and installation of water-saving consumer fixtures to reduce household demand.

A feasible solution to significantly reduce the gap between supply and demand emphasizing demand management can be developed; however, the impact on the socio-economic framework of the West Bank may be great. Restriction of agricultural growth will have serious impact on the West Bank economy, which is presently agrarian based. Even if subsidies and compensation are given to land-owners not to irrigate, the labor and markets associated with irrigated agriculture will be negatively impacted.

Possible advantages and disadvantages of the axis of demand management are summarized below.

Table 8

Advantages and disadvantages of the axis of demand management

Advantages	Disadvantages
Relatively inexpensive method	Potentially high socio-economic cost
Technically easy to implement	May require farmer subsidies for implementation
Not dependent on water rights	

Strategies to move a way from water crisis

- Secure the Palestinian water rights
- Strengthening water institutions to be able to govern water efficiently and effectively
- Implement a combination of water supply and demand measures
- Reforming and modernizing agriculture
- Promoting co-operation between countries sharing water resources
- Improving sanitation and protecting water quality
- Generating knowledge and helping in the uptake of existing knowledge in relation to water use efficiency and water quality.

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Water Resources Management of El-Zabadani Basin

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Water Resources Management of El-Zabadani basin [1]

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Abstract

The study aims to build a mathematical model to simulate the groundwater flow system for one important sub-basin in Syria. This model will be used as a tool for the decision maker to manage and set up proper plan for the basin water resources. The water balance components for the aquifer were computed by the model. These computations show that the total inflow to the basin is estimated at about 675 Mm^3/year distributed within components of the horizontal flow (672 Mm^3/year), and recharge (2.7 Mm^3/year). The model was used to test two scenarios, the first one presented the case of continuous drought, and the second one represents more optimistic situation were sort of steady state condition prevails in the basin. The study showed that the area has limited water resources, which are highly depended on the amount of rainfall rather than on the amount of exploitation. The study gave some recommendations for sustainable water resources management.

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Introduction:

Since late seventies ACSAD started to apply computer simulation models for analyzing flow in groundwater systems. Numerical groundwater flow models have been constructed to develop an understanding of the groundwater flowing systems, evaluate the effects of development on groundwater resources and support groundwater management. ACSAD has developed several sub-regional models in areas confronted with problems of depletion or rapid deterioration of groundwater quality in the Arab countries. This study is one of the important studies carried out in Syria.

Zabadani sub-basin is one of the most important basins in Syria, it is considered as a strategic source of drinking water for Damascus City. The historical Barada spring is flowing from this basin with an average rate of 3 m^3/sec (Fig. 1).

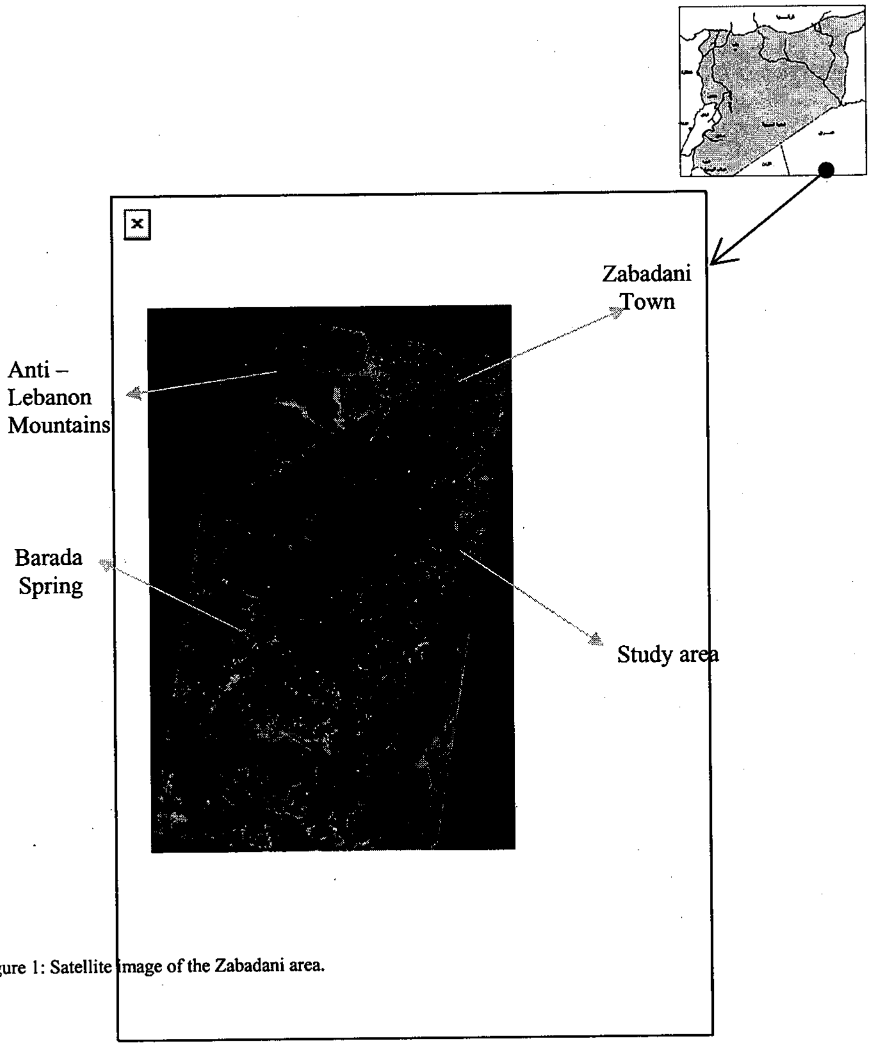

Figure 1: Satellite image of the Zabadani area.

This study aims to build a mathematical model, to simulate the groundwater flow system and produce a tool for the decision maker to manage and set up proper plan for the basin water resources. This was carried out by defining the water balance components and predicting the effect of the present and proposed plans on the water system of the aquifer.
The study is carried out by ACSAD (Arab Center for the Studies of Arid zones and Dry lands) with the cooperation of GORS (General Organization of Remote Sensing), and coordination with the GDBAB (General Directory of Barada & Awaj Basin) & DAWSSA (Damascus Water supply & Sewerage Authority). The study started at March 2000 and completed at June 2002. The full report is published by ACSAD upon completing the study (Rofail *et al*, 2002).

The work plan is implemented according to following five consecutive phases:

- Collection of the available data and evaluation of the present status
- Performing field survey to fill the gaps of present status. This included the periodical measurements of water levels during the calibration period.
- Establishing databases linked to GIS so the data will be readily available to the mathematical model.
- Running and calibrating of the model, and
- Testing the response of the aquifer water system according to the various scenarios of the future plans.

Remote sensing technique refines the geological map and establishing the lineaments map of the area. Moreover, satellite photos with the help of ground check, helped in defining the agricultural practices and produce the thematic maps; land and water use map, and plant cover map.
Around 2300 exploitation wells have been recorded by the field survey. Accordingly the monthly groundwater exploitation has been estimated. Groundwater level was monitored periodically (Table 1) from selected 80 wells network (Fig. 2). All the data have been collected and organized into three data banks. First one covers all available data of the exploratory wells, second for exploitation wells, and the last one for observation network.

The previous data have been linked to GIS (Arc/Info) and accordingly various layers have been designed (such as layers of: volumes of irrigation water, volumes of pumped water...etc). Figure 3 shows an example of such layer where the amount of groundwater exploitation on August been estimated according to the exploitation wells data bank. The monthly water levels maps have been plotted. The main directions of groundwater flow were from north to south-west along Barada river and from mountains on the east towards Barada spring as shown in figure 4.

Table 1: Measured water table level.

		Water Level (m.a.s.l)													
		2000				2001									
WELL_ID	Total depth	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
1	140	1083.4	1083.28	1083.27	1083.17	1083.55	1085.59	1090.9	1091.42	1091.73	1089.5	1086.88	1082.65	1079.45	1078.5
2	48	1083.88	1083.86	1083.99	1083.76	1084.45	1085.68	1091.53	1092.63	1092.23	1090.03	1086.68	1082.88	1079.98	1079.13
3	98		1087.74	1087.82	1087.67	1089.42	1089.72	1095.62	1096.49	1096.12		1087.19	1086.42		1078.67
4	20	1115.3	1117.5	1120.9	1125.98	1124	1125.2	1127.6		1123.2		1115.2	1115		1114.95
5	15	1113.15	1124.7	1125.16	1125.45	1125.72	1126.15	1127.05	1128.02			1118.45	1122.77	1123.85	1123.65
6	16.5	1112.51	1115.18	1119.4	1121.71	1122.29	1123.56	1124.16	1122.78	1122.86			1113.66	1114.46	1113.36
7	17	1123.45	1123.3	1123.45		1124.54	1125.4	1125.1	1125.03	1124.42	1123.45	1124.4	1123.9	1124.25	1123.55
8		1129.5	1129.55	1129.28	1129.77	1130.15	1131.73	1131.58	1132.18	1132.41	1131.13	1129.83			
9	90		1089.71	1090.78	1090.78	1093.03	1096.06	1101.86	1102.59	1100.38		1088.96	1086.66	1083.36	1083.81
10	70	1084.21	1084.23	1084.22	1084.11	1084.71	1086.56	1092.01	1092.91	1092.59	1090.26	1088.66	1083.06		1079.41
11	10	1111.25	1112.2	1111.34	1111.7	1112.57	1115.35	1115.05		1111.43	1113.25	1112.85	1111.3	1109.7	1111.64
12	10	1118.35	1118.67	1116.3	1121.9	1123.15	1125.35	1125.55	1124.7	1121.15		1118.85	1117.47		1118.4
13	14	1113.96	1115.43	1117.64	1118.51	1119.09	1119.36	1118.96	1119.29	1117.26	1117.21	1114.96	1113.96	1115.61	1115.96
14	293		1042.8	1042.71	1042.17	1060.23	1067.26	1075.66	1070.11	1071.2	1072.26	1057.49	1049.76	1047.99	1043.26
15	100	1083.98	1083.93	1083.82	1083.66	1084.23	1086.18	1091.66	1092.33	1092.18		1087.46	1082.83	1079.91	1079.08
16	55	1084.06	1083.81	1083.86	1083.69	1084.57	1085.81	1091.61	1092.49	1092.21	1089.91	1087.46	1086.26		1079.04
17	50	1083.97	1084.02	1084.02	1083.87	1084.43	1087.07	1091.87	1092.52	1092.37	1089.97	1087.6	1083.47		1079.12
18	40	1105.73	1087.65	1087.68	1087.51	1088.08	1089.48	1095.68	1096.18	1095.58	1093.78	1090.98	1086.33	1083.48	1082.68
19	150		1088.16	1088.09	1087.94	1088.58	1090.09	1095.74		1096.39		1065.04		1083.92	1083.09
20	10	1105.85	1106.05	1106.75	1107.05	1107.25	1107.75	1107	1106.95	1107.05	1106.65	1105.15	1106.35	1106.5	1106.2
21	60	1087.61	1099.31	1102.31	1104.39	1106.33	1108.16	1109.25	1109.51	1108.11	1103.96		1095.21	1094.26	1094.81
22	220	1121.03	1121.03	1121.08	1121.17	1121.28	1121.38	1121.33	1121.23	1121.18	1120.93	1120.9	1120.43	1120.56	
23	60	1094.04	1093.96	1096.91	1099.71	1100.44	1103.19	1104.29	1104.81	1103.69					
24	10	1108.4	1108.95	1108.05	1109.32	1109.7	1110.1	1109.75	1109.35	1108.6	1107.15	1106.6		1107.7	1108.5
25	10	1101.01	1101.63	1102.21	1103.71	1104.48	1106.78	1107.61	1107.11	1106.41		1102.56	1105.81	1098.51	1102.16
26	18	1087.92	1095.92	1098.25	1099.09	1100.37	1102.72	1103.47	1103.06	1101.92			1101.07	1089.62	1097.72
27	100	1097.02	1097.39	1097.73	1098.12	1099.25	1101.07	1101.07	1100.75						
28	100	1088.57	1088.59	1088.68	1088.31	1088.99	1091.07	1096.77	1097.4	1096.92	1094.67	1092.47	1087.12	1084.64	1083.77
29	100	1087.61	1087.73	1090.75	1087.59	1088.16	1089.61	1095.51	1096.21			1091.91	1085.91	1083.57	1075.71
30	53	1086.71	1086.69	1086.76	1086.63	1087.21	1088.66	1094.56	1095.31	1095.11			1085.51		1081.81
31	70	1082.22	1083.04	1083.04	1082.96	1083.44	1084.92	1090.95	1091.57	1091.37			1081.77	1079.07	1078.27
32	110	1088.74	1088.64	1088.69	1088.51	1089.14	1090.59	1096.64	1097.24	1097.04		1092.44	1087.64	1084.92	1083.91
33	120	1094.92	1088.67	1088.58	1088.5	1089.08	1090.52	1096.62	1097.17	1096.97	1094.74	1092.62	1087.62	1084.98	1083.89
34	36	1089.89	1088.59	1088.62	1088.44	1088.99	1090.49	1096.54	1097.14	1096.96	1094.69	1092.04	1087.49	1084.69	1078.24
35	60	1208.09	1219.19	1219.53	1219.79	1220.34	1221.69	1224.47	1225.24	1225.19				1218.44	1217.22
36	100	1087.47	1086.82	1087.83	1087.67	1088.29	1089.72	1095.82	1096.32	1096	1093.95	1089.67			1082.47
37	85	1088.7	1088	1088.47	1088.3	1088.96	1095.1	1096.35	1096.9	1096.6		1092		1087.85	1083.05
38	127	1079.66	1088.29	1088.39	1088.27	1088.91	1091.68	1096.21	1096.98	1096.81	1094.41		1087.26	1084.74	1083.06
39	75	1087.42	1088.32	1088.75	1088.6	1089.25	1090.27	1094.95	1093.6	1094.58	1091.72	1090.5	1085.7	1082.23	
40	9	1093.08	1097.56	1097.98	1098.03	1099.88	1100.98	1100.58	1100.08	1099.66	1098.58	1094.53	1096.5	1093.26	1096.43
41	10.8	1097.88	1097.31	1096.95	1097.03	1099.06	1100.08	1099.48	1099.27	1098.98	1096.58	1093.08	1097.28	1097.66	1097.83
42	20	1095.91	1095.73	1096.06	1096.71	1098.31	1099.66	1100.11	1099.86	1098.31	1098.68	1096.01	1097.19	1095.76	1095.56
43	10	1098.2	1098.65	1098.85	1100.17	1100.45	.1101	1101	1100.4	1099.65	1098.63	1096.4	1095.4	1094.8	1094.95
44	125		1090.01	1089.81	1089.59	1090.04	1091.19	1096.44	1097.56				1089.44		
45	140	1045.17	1049.47	1051.09	1053.45	1054.37	1058.92	1060.05	1059.8	1058.15	1051.67			1046.1	1045.12
48	100	1063.21	1068.44	1075.84	1080.41	1085.89	1092.06	1093.56	1099.71					1063.78	1063.26
49	130	1078.77	1086.76	1086.69	1086.75	1087.13	1088.62	1090.36		1095.76				1083	
51	75	1089.38	1091.21	1091.05	1090.93	1091.48	1094.43	1100.7	1097.48	1095.5	1092.2		1083.98		
52	125	1089.33	1088.63	1088.6	1088.38	1088.93	1090.33	1096.23	1096.91	1096.41	1095.6	1093.53	1088.83	1085.88	1084.13
53	10	1096.19	1095.54	1095.97	1095.98	1096.39	1098.29	1098.29		1097.69	1092.14				1091.89
54	100	1088.76	1088.44	1088.48	1088.23	1088.89	1090.26	1096.36	1096.91	1096.83	1094.65	1092.21	1087.34	1084.46	1083.01
55	100	1088.74	1088.39	1088.47	1088.29	1088.89	1090.31	1096.34	1097.04	1096.82	1094.74	1092.21	1084.44		1083.14
56	100	1214.41	1215.43	1203.33	1221.09	1221.11	1221.63	1222.78	1221.68	1219.93		1190.98		1185.73	1206.38
62	50			1765.85		1768.35		1773.65	1774.25	1773.73	1773.45				1763.1
63	155	1044.6	1042	1044.9	1046.2	1047.9	1048.7	1053.1		1057			1040.1	1040.45	1036.57
65	75	1046.32	1049.07	1050.47	1051.85	1053.62	1056.85		1060.27	1061.62	1053.99		1041.67	1043.22	1040.87
66	147		1050.58	1052.01	1053.76	1054.38	1055.71	1057.77		1058.29				1045.96	1045.86
67	205	1056.23	1078.77	1059.86	1062.78	1066.23	1062.23	1062.35		1060.33	1058.53	1055.53	1054.68	1049.86	1055.46

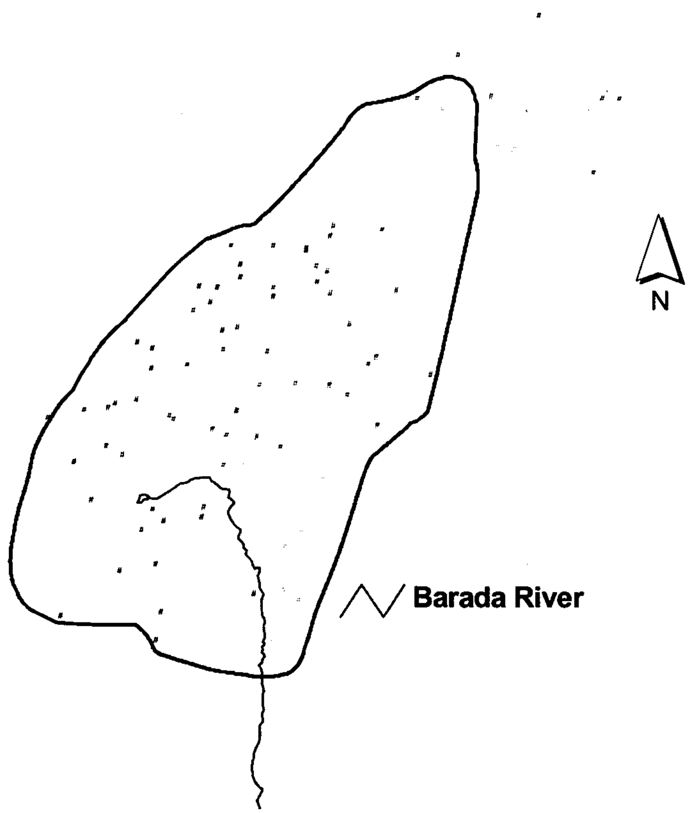

Figure 2: Network of observation wells.

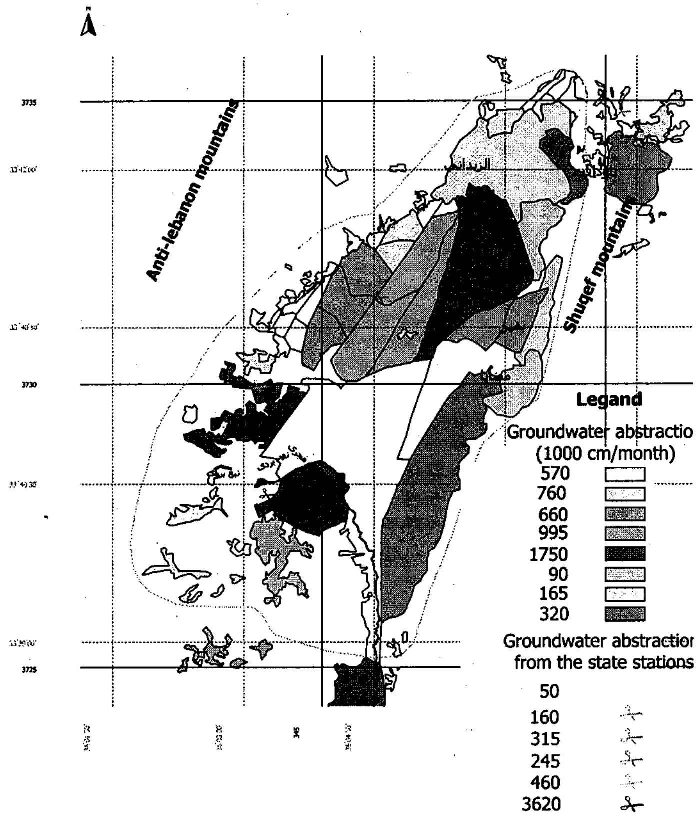

Figure 3: Groundwater exploitation in August 2001(x 1000 cubic meter/month).

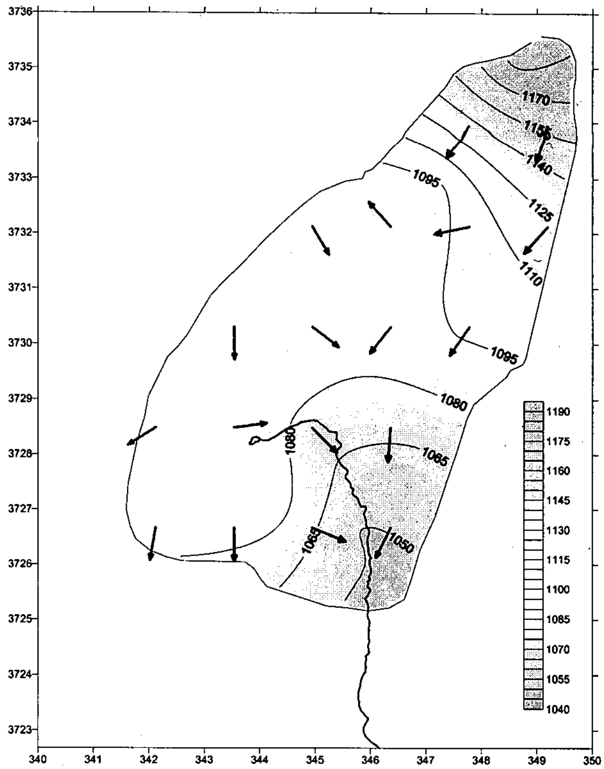

Figure 4: Water table map for October 2000 (m.a.s.l).

Mathematical model preparation

Theoretical Background:

During the past several decades, mathematical models for analyzing flow and solute transport in groundwater systems have played an increasing role in the evaluation of alternative approaches to groundwater development and management. These models rely upon the solution of groundwater flow equations. The basic law of flow is Darcy's laws', and when it is put together with an equation of continuity that describes the conservation of fluid mass during flow through a porous medium, a partial differential equation of flow is the result. The partial differential equation of flow for transient flow through a saturated anisotropic porous medium is;

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) - W = S_s \frac{\partial h}{\partial t}$$

where,

K_x, K_y, K_z	are the hydraulic conductivities in the direction of x, y, z respectively (LT^{-1}),
S_s	is the specific storage (L^{-1}),
W	is a volumetric flux per unit volume and represents sources and/or sinks of water (T^{-1})
h	is the hydraulic head (L), and
t	is the time (T)

The previous partial differential equations can be solved mathematically using either analytical solutions or numerical solutions. Many analytical solutions have been developed for the flow equation; however, obtaining the exact analytical solution to the partial differential equation requires that the properties and boundaries of the flow system be highly and perhaps unrealistically idealized. Alternatively, for problems where the simplified analytical models no longer describe the physics of the situation, the partial differential equations can be approximated numerically. In so doing, the continuous variables are replaced with discrete variables that are defined at grid blocks or nodes. Thus, the continuous differential equation, which defines hydraulic head everywhere in the system, is replaced by a finite number of algebraic equations that defines the hydraulic head or concentration at specific points. This system of algebraic equations generally is solved using matrix techniques. This approach constitutes a numerical model.

Two major classes of numerical methods have come to be well accepted for solving the groundwater flow equation. These are the finite-difference methods and the finite-element methods. Comprehensive treatments of the application of these numerical methods to groundwater problems are presented by Wang and Anderson (1982). Both of these numerical approaches require that the area of interest be subdivided by a grid into a number of smaller subareas (cells or elements) that are associated with nodal points (either at the centers or peripheries of the subareas).

Each approach has advantages and disadvantages, but there are very few groundwater problems for which either is clearly superior. In general, the finite-difference methods are simpler conceptually and mathematically, and are easier to program (Konikow and Reily 1999).

The code we used was MODFLOW-96 of Harbaugh and McDonald (1996), which is a most popular and comprehensive deterministic groundwater models available today. MODFLOW is an implicit finite-difference solution to the three-dimensional flow equation. The full description of the model is available in McDonald and Harbaugh (1988).

The conceptual model:

A conceptual model is a simplified representation of the essential features of the physical hydrogeological system, and its hydrological behaviour, to an adequate degree of detail. The key to efficiency and accuracy in modeling a system probably is more affected by the formulation of a proper and appropriate conceptual model than by the choice of a particular numerical method or code (Anderson & Woessner 1992).

The conceptual model studied area has been built according to the prevailing hydrogeological and geological conditions. These conditions were defined in a study done by USSR Ministry of Land Reclamation and Water Management Moscow (1986). The hydrogeological map (Fig. 5) shows that there are two main groups of deposits, the first one is the Cretaceous *(Cr)* & Jurassic *(Jr)* deposits which are outcrop in the west and east of the model area. The second one is the Quaternary-Neogene *(Q-N)* deposits which are located in the middle of the model area at the graben formed by the tectonic structure. Figure 6 shows an east-west cross section to the model area produced by TECHNOEXPORT study at 1986. The aquifer was divided into two layers; the first layer included the above 300m and the Quaternary-Neogene *(Q-N)* deposits. This 300m depth was chosen according to the previous studies, which concluded that this depth is the most active depth hydraulically. The lower layer consists of Cretaceous *(Cr)* & Jurassic *(Jr)* deposits. It was considered that these layers are hydraulically connected. The model grid has been designed with various densities according to the available data and extent of external activities. The previous GIS layers then transferred to the model grid.

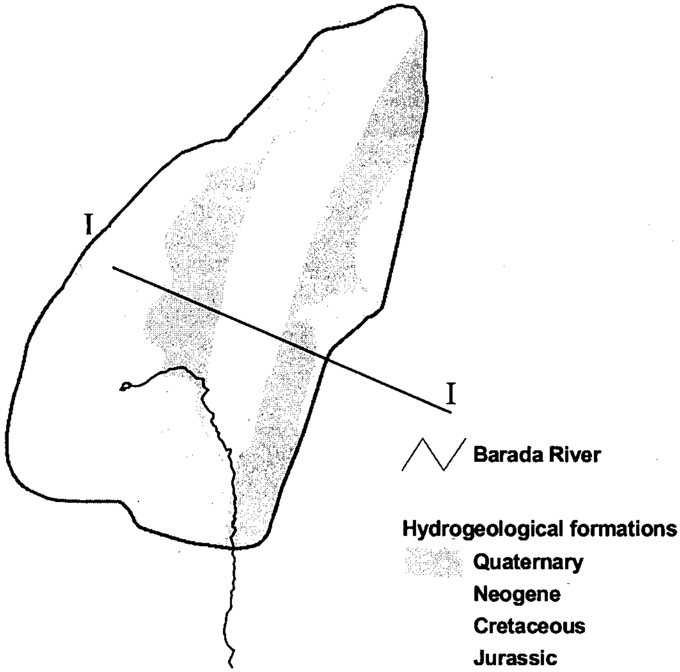

Figure 5: Hydrogeological map of the area.

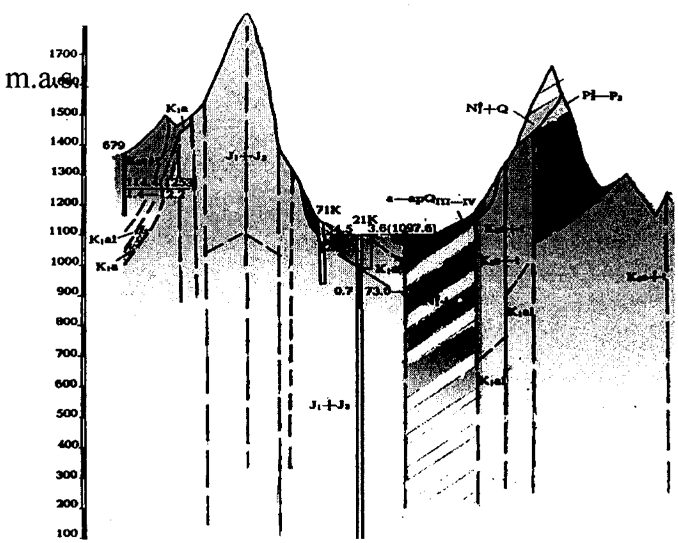

Figure 6: Cross Section I-I .

Partial differential equations representing the water flow for the whole system was formulated taking into account all the Basin's boundary conditions and external stresses. The boundary conditions assumed to be Time-Variant Specified-Head. Barada spring was defined as a drain cells and the conductance coefficient estimated during calibration. The procedure of the mathematical solution of differential equations was defined using the implicit scheme algorithm, which is unconditionally stable.

The Processing Modflow ٥,١ (Chiang & Kinzelbach ٢٠٠١) with MODFLOW-1996 code (Harbaugh and McDonald, 1996) was applied in preparing and running the model. The area has been simulated in a network of cells (653 cells) covering an area of 49.2 Km^2. The cells carry the various data of engineering dimensions of the two concerned layers in the conceptual model and the initial values of hydraulic parameters. The GIS and electronic tabulation systems were used in building the model input data in compatible way with the used modeling system.

The locations and quantities of groundwater exploitation existing on the network were simulated according to year 2000-2001 and the results of the field survey carried out in the area by GORS. The total exploitation amount was approximately 69 million m^3 per year. The groundwater recharge from rainfall was taken into consideration and calculated depending on the soil type, lineaments, and depth to water. The amount reached to about 2.73 Mm^3/year.

Calibration of the model

Calibration is the process by which the independent variables of the model are adjusted, within realistic limits, to produce the best match between simulated and measured data (from groundwater level monitoring). The calibration of a deterministic groundwater model is often accomplished through a trial and error adjustment of the model's input data (aquifer properties, sources and sinks, and boundary and initial conditions) to modify the model's output. However, the hydrologic experience and judgment of the modeler continues to be a major factor in calibrating a model both accurately and efficiently.

The model was calibrated for steady and non-steady state. During steady state the calibration aims to develop a broad hydraulic conductivity distribution during steady hydrological conditions. Following steady state calibration, transient calibration was undertaken to calibrate aquifer storage parameters, and fine-tune aquifer hydraulic properties. To achieve this, the simulation time (one complete hydrologic year from Oct. 2000 to Sep. 2001), was divided into 12 stress periods (one for each month). Each stress period was divides into 10 time steps. The hydraulic parameters were varies in successive model runs, until field data (heads) match with computed data reasonably well.

Based on the calibration of the model, the values of hydraulic parameters for the first and second layers were defined. The value of horizontal hydraulic conductivity in the upper layer ranged between 0.7 m/day in the *Q-N* deposits to 275 m/day in the highly fractured areas around the Barada spring (Fig. 7). The value of vertical hydraulic conductivity of the upper layer ranged between 0.3 to 16 m/day in corresponding with the distribution of the horizontal conductivity. The values of specific yield of this layer ranged from 0.04 to 0.07.

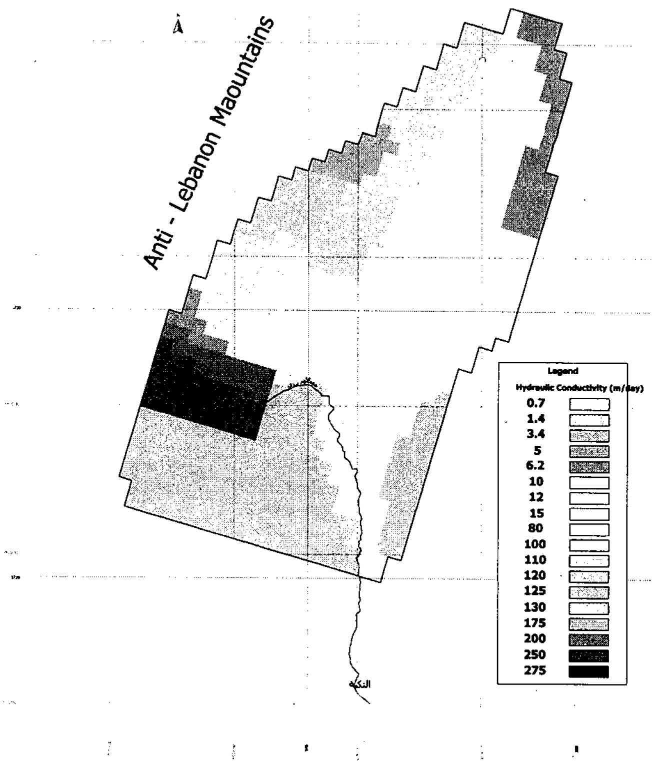

Figure 7: Distribution of horizontal hydraulic conductivity (m/day) of the first layer.

The second layer was more homogeneous and less fractured, the value of horizontal hydraulic conductivity reduced to 5 m/day while the vertical hydraulic conductivity was about 1 m/day and the storage coefficient was close to 0.0001.

Following calibration, water balance components for the whole aquifer was computed. Such computations show that the total inflow to the basin is estimated at about 675 Mm^3/year distributed within positive components of the horizontal flow (672 Mm^3/year), and recharge (2.7 Mm^3/year). The value is matched by an equivalent quantity of outflow distributed within negative outflow components of horizontal flow components (612 Mm^3/year), spring outflow (9.9 Mm^3/year) and exploitation (69 Mm^3/year).

Prediction

Due to the short length of calibration period and to the limited number of observation wells, which have historical records, the prediction period would be relatively short (three years) and the relevant results will be defined in general way.
Two scenarios were tested, the first one presented the case of continuous drought, and the second one represents more optimistic situation were sort of steady state condition prevails in the basin.
During the first scenario the water table continued to fall down at the same rate of the previous four years. This rate was estimated from the readings of two wells (Fig. 8). These wells located on the east of the area and were the only wells which have old record. No additional exploitations were assumed and all other activities were as of those adopted during calibration. An average groundwater draw down of nine meters was predicted after three years.
For the second scenario a new exploitation sites were assumed to pump additional drinking water for Damascus City from six new sites. This pumping water was increased gradually by fifty percent each year and reached 56 Mm^3/year at the third year. The model showed that a maximum drawdown of two meters was predicted after three years at the exploitation sites (Fig. 9).

It should be concluded that the results derived from any scenario are subject to the adopted conditions and that any scenario should be carried out carefully with continuous monitoring of groundwater level.

General Recommendations

The study showed that the area has limited water resources, which are highly depended on the amount of rainfall rather than on the amount of exploitation. The model is a presentation of the water system complex that is strongly depends on the available hydrogeological information. The accuracy of the model results can't exceed the accuracy of the input data itself. Therefore it is important to conduct more detailed studies whenever we like to carry out any new exploitation schemes <u>especially</u> near the Barada spring area where karstic structure exist.

Since the calibration was done for only one year it is necessary to recalibrate the model periodically and re-examine the hydraulic parameters and the water balance of the system. This should be done on schematic way by the responsible authorities.

As is mentioned before, it is of great important for better prediction to continue monitoring of water levels (monthly at least) and to enhance the existing groundwater monitoring network. New standard piezometers should be drilled into the Jurassic aquifer and a correlation equation between rainfall and water levels have to be defined and improved continuously.

It has been noticed that the Groundwater pollution is increasing. Therefore, a special monitoring scheme should be constructed and a new regulation should be implemented to stop irrigating by raw sewage water. It is essential to establish treatment plan for the sewage water, so the effluent water can be used safely for irrigation. Also, since the Barada spring is now considered as a major drinking water supply, the spring catchment area should also be strongly protected.
Irrigation methods should be improved to enhance the water use efficiency and reduce the amount of exploited water. Awareness rising program should be organized to the farmers to encourage the applying modern irrigation systems and discourage applying of sewage water in irrigation.

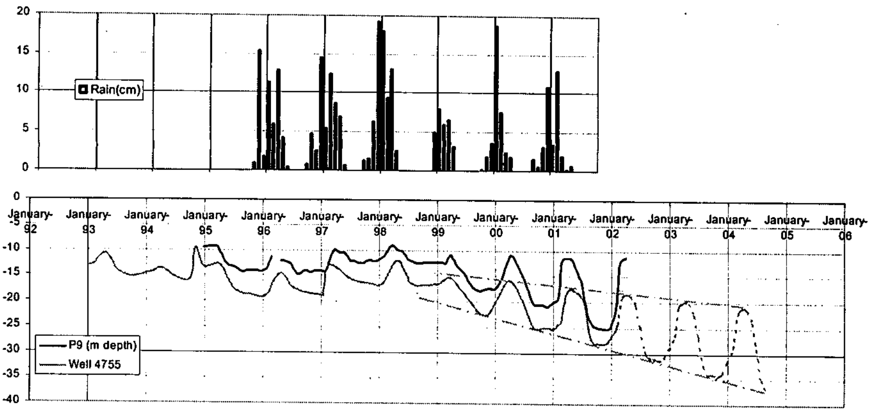

Figure 8: Drawdown of groundwater in two representative wells.

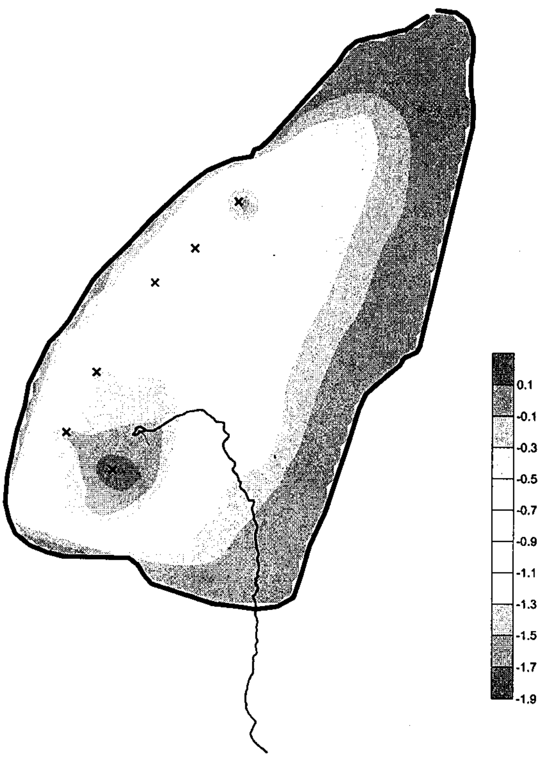

Figure 9: Groundwater drawdown at the end of the second scenario.

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Application of Horizontal Drilling Technology in Groundwater Projects

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Application of Horizontal Drilling Technology in groundWater Projects

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and Abdulrahman A. Alquraishi**

Abstract

Drilling and production of horizontal wells are the most significant technological breakthrough of the oil and gas industry in the eighties. Since then it has been widely used throughout the world for oil and gas production. When compared to a vertical well, horizontal well proved to be one of the most effective choice in increasing production rates and improving reserves and hence increase the current value of the field under hand. In this paper a theoretical study is presented to study the applicability of this technique by comparing water productivity as a function of pressure drawdown of a Saudi fresh water formation using hypothetical vertical and horizontal wells. The considered scenario shows that productivity is two to six times higher using single horizontal well rather than four vertical wells depending on the drainage radius of the horizontal well. This proves that such drilling application is very promising in water formations. It can boost the production with minimal pressure drawdown and hence save a huge amounts of money and reduce the degree of fluid disturbance (conning and saline water intrusion) that may occur due to high pressure drawdown caused by excessive water production.

Keywords
Groundwater, Wasia, Horizontal well, Drawdown, Fresh water.

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Introduction

Saudi Arabia in general is one of hottest and most arid countries in the world, with summer temperatures reaching 46°C and an average rainfall of 120 mm per year. Water resources in Saudi Arabia are conventional which includes ground water and surface water, and non-conventional such as desalinated seawater and treated waste water. About 88 percent of the water consumption in Saudi Arabia is met by groundwater. The western coastal plain (Tihama) receives 60 percent of the country's total rainfall. Rainfall in this region provides an average supply of approximately 1.85 billion cubic meters of water, accounting for approximately nine percent of the total annual water consumption. Desalinated water production is approximately two and a half million cubic meters per day, constituting approximately 2.5 percent of annual water consumption [1]. Table 1 lists the major ground water formations in Saudi Arabia. All wells drilled in these formations for groundwater production are vertical.

Table. 1 Major groundwater aquifers in Saudi Arabia [2].

Aquifer	Water depth, m	Thickness, m	Productivity, 10^3 m^3/day	Location	Rock type
Al-Saq	150 – 1500	650	8640	Central-North	Sandstone
Wajid	150 – 900	600	3456 – 6912	Southern	Sandstone
Tabuk	60 – 2500	1072	1296 – 1728	Central-North	Sandstone and Shale
Minjur	1200 – 2000	315	5184 – 10368	Central	Sandstone
Dhruma	100	375	5184 – 10368	Central	Sandstone and Limestone
Biyadh	30 – 200	425	2160 – 4320	Northern	Sandstone
Wasia	100 – 800	150	7344 – 9504	Central-East	Sandstone and Shale
Umm-Er-Radhuma	100 – 400	330	4320 – 8640	Eastern	Limestone
Dammam	160 – 200	80	605 – 1900	Eastern	Limestone
Neogene	50 - 100	100	4320 - 8640	Eastern	Sandstone and Limestone

High water production rates from vertical wells yield excessive drawdown. When exceeding the critical drawdown value, water quality will be reduced and the stability of the productive formation adjacent to the well is altered. Due to the high demand of fresh water, conservation and development plans must be set to produce fresh water at maximum rates without disturbing the physical and mechanical properties of groundwater aquifers [3] and maintaining the quality of the produced water. The previously mentioned goals can be achieved by applying the technology of horizontal drilling.

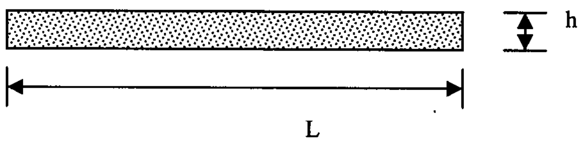
HORIZONTAL WELL TECHNOLOGY

Although directional drilling has been applied in the oil industry for many decades, horizontal well technology has not fully developed until late 1980's. Thousands of horizontal wells have been drilled in the period from 1985 up to date in different parts of the world.

In Saudi Arabia, now there are more than 200 horizontal wells drilled by Saudi Aramco and the Arabian Oil Company Limited (now changed to Saudi Aramco for Overseas Operations). The number of horizontal wells in Saudi Arabia is on the rise and is expected to account for more than 60% of the new planned wells.
Horizontal drilling is practiced in the oil and gas industry to overcome certain problems. Among those applicable to water formations are:

1- Thin pay zone in order to increase the contact between the drilled section and the water bearing formations (see Figure 1).
2- Poor knowledge of the lithology away from the wellbore.
3- Avoiding surface restriction.
4- High-pressure drawdown resulting in conning and formation instability.
5- Increasing recovery with minimal pressure drop.

Horizontal wells proved to be one of the most effective choices in increasing production rates and improving reserves and hence increase the current value of the field under hand. The objective of this study is to compare the productivity of hypothetical vertical and horizontal wells in Wasia groundwater aquifer in the central province of Saudi Arabia.



Vertical well:	h = Maximum layer thickness. Maximum flow surface area = $2 \pi r h$
Horizontal well:	L = Maximum layer length. Maximum flow surface area = $2 \pi r L$
Ratio of fluid flow surface area:	Horizontal / Vertical = L/h

Figure 1. Available flow surface areas for vertical and horizontal wells drilled in the same formation.

Modelling of Fluid Prodction
Radial fluid flow into a vertical wellbore in a homogeneous and isotropic formation is calculated using Darcy equation governing fluid flow in porous media:

$$Q_V = \frac{7.081 * k * h * \Delta P}{\mu * \beta * \ln\left(\frac{r_d}{r_w}\right)} \qquad \text{.......(1)}$$

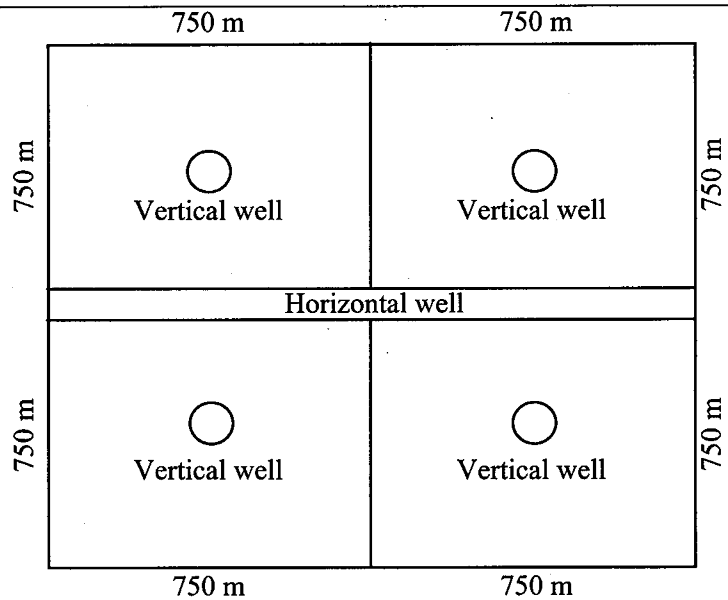
Under similar conditions mentioned above, fluid flow into a horizontal wellbore is calculated using the following formula [6]:

$$Q_V = \frac{7.081 * k * h * \Delta P}{\mu * \beta * \left\{ \ln\left(\frac{1 + \sqrt{1 - \left(L/_{2 * r_d} \right)^2}}{\left(L/_{2 * r_d} \right)} \right) + \frac{h}{L} * \ln\left(\frac{h}{2 * \pi * r_W} \right) \right\}} \quad ....(2)$$

From the above equations, it is noticed that pressure drawdown in vertical well is proportional to (Q/h) whereas in horizontal well it is proportional to (Q/L). As a result pressure looses for a given flow rate is a considerably less in horizontal well.

Comparison Study

Wasia ground water aquifer data was chosen to conduct the comparison analysis between vertical and horizontal wells. Wasia water field is one of the biggest water projects in Saudi Arabia that was constructed to meet water demand of Riyadh city. The well field is designed to supply more than 220,000 m^3/day. The well field is located 110 kilometers northeast of Riyadh. It consists of 62 vertical production wells and three vertical observation wells. The wells are located in four parallel rows extending northwest-southwest and both of the rows and wells are 750 meters apart [7]. The layout map of four wells of Wasia well filed and a single hypothetical horizontal well is shown in Figure 2.



Case 1: 4 vertical wells. Drainage area = 750 X 750 X 4 = 2250000 m^3.

Case 2: a single horizontal well. Drainage area = 1500 X 1500 = 2250000 m^3.

Figure 2. Drainage areas for hypothetical vertical and horizontal wells used in the comparison study.

Equations 1 and 2 have been used to calculate pressure drop (drawdown) for various production rates of water from firstly four vertical wells and secondly form a single horizontal well from an equivalent drainage area. Ground water aquifer rock and fluid properties as well as wells dimensions are shown in Table. 2.

Table 2. Rock, fluid and wells properties of the groundwater aquifer used in the comparison study.

r_d = 423 m (1388 ft) for a single vertical well.		
r_d = 846 m (2776ft) for a single horizontal well.		
L = 1500 m (4922 ft).	h = 150 m (492 ft).	r_w = 0.20 m (0.66 ft).
k = 400 md.	μ = 1 cp, for water.	β = 1, for water
Aquifer depth = 1312 m (4305 ft).		
Aquifer water pressure = 144 atm (2115 psi).		

Pressure drawdown for a single vertical well is calculated using Eq. 1 and multiplied by four assuming the existence of four vertical wells in the drainage area. This calculation was repeated at different production rate. For comparison, a single horizontal well replaced the four vertical wells using the same drainage area. The same values of the production rates used in the case of vertical wells were used in Eq. 2 to calculate the drop in the aquifer pressure (drawdown). The resulted drawdown data was plotted versus the production rates as shown in Figure 3. It can be seen that a production rate of 180000 m^3/day using the four vertical wells requires a drawdown approximately four times greater than that required to produce the same quantity from a single horizontal well.

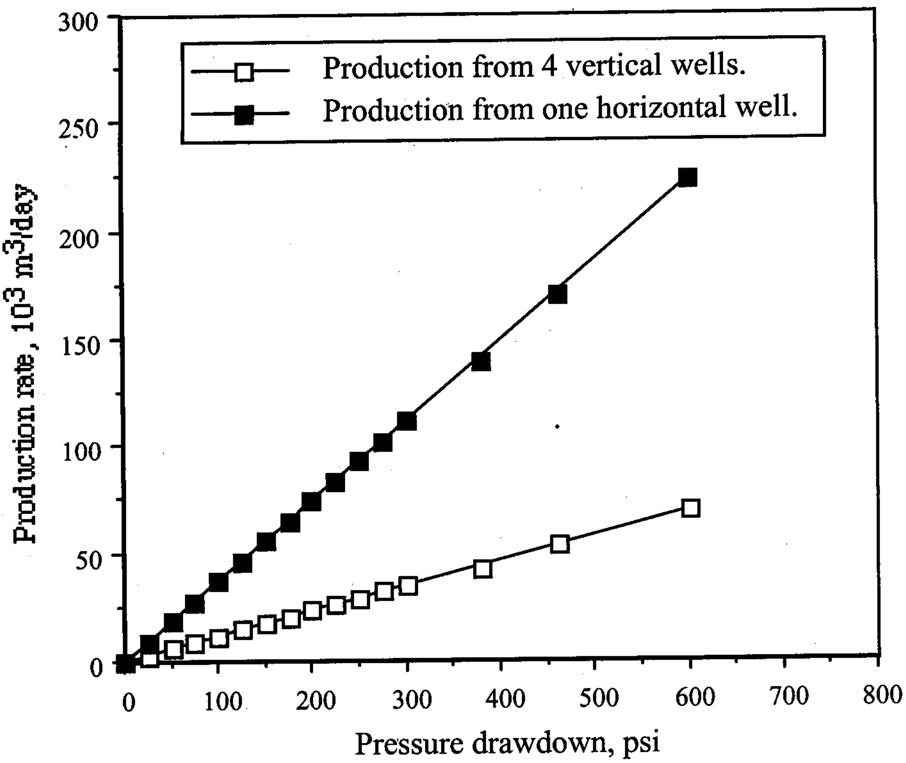


Figure 3. Relationship between pressure drawdown and water production rate for vertical and horizontal wells.

Economical Factor

In the early practice of horizontal drilling, cost was high when compared to vertical wells in addition to loss of time due to hazards and lack of experience in this new technology. Nowadays, drilling and completion of horizontal and vertical wells are relatively similar due to the huge technological development in drilling tools manufacturing and the huge experience gained throughout the years. The marginal cost ratio between a horizontal to vertical wells is reduced to a ratio of 1.5. In Saudi Arabia cost was reduced by 40 % in four years time between 1990 and 1993 without scarifying water production. The difference in drilling and completion cost can be overcome by reducing the number of wells drilled to drain a certain area and the increase in reserves and production rates.

Conclusions

Based on the analysis conducted in this study, the following conclusions are obtained:

- For the same pressure drawdown in the same formation and drainage area, a single horizontal well yields four times higher water production than that obtained by four vertical wells

- The utilization of horizontal wells reduces the cost of maintenance and observation.

- The utilization of horizontal wells provides higher water production at minimal disturbance of water level and formation properties.

- The application of horizontal drilling technology is therefore highly recommended in groundwater projects.

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NOMENCLATURE

r_d = Radius of the drainage area, ft.

r_w = Wellbore radius, ft.

h = Formation thickness, ft.

k = Formation permeability, md.

μ = Fluid viscosity, cp.

β = Formation volume factor, bbl/STB.

ΔP = Pressure drawdown, psi.

L = Length of the horizontal section, ft.

Q_v = Fluid flow (production) rate from a vertical wellbore, bbl/day.

Q_h = Fluid flow (production) rate from a horizontal wellbore, bbl/day.

Hydrogeology, Groundwater Chemistry and Isotope Hydrology of the Quaternary Liwa Aquifer in the Western Region of the United Arab Emirates

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HYDROGEOLOGY, GROUNDWATER CHEMISTRY AND ISOTOPE HYDROLOGY OF THE QUATERNARY LIWA AQUIFER IN THE WESTERN REGION OF THE UNITED ARAB EMIRATES

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ABSTRACT

The present hydrogeological investigation of the Quaternary sands in the Western Region of United Arab Emirates revealed the presence of a local, fresh water aquifer in the Bu Hasa area, and confirmed a similar feature between Liwa and Madinat Zayed. Because of the striking similarity of hydraulic properties, chemistry and natural isotopes of the groundwater at Bu Hasa and Liwa, the aquifer in both areas is dealt with as a single aquifer named the "Quaternary Liwa aquifer".

Two fresh water mounds belonging to the Quaternary Liwa aquifer represent relics of an old, large aquifer originated during past pluvial periods and occupy the northwestern part of study area. A large, elliptical (40 km wide and 120 km long) mound occurs between Madinat Zayed and Liwa Crescent, and a small, oval mound (40 km average diameter) exists between Habshan and Bu Hasa camp. The depth to groundwater varies between a few meters and 50 m at Liwa, and from 24 m to 52 m at Bu Hasa. The aquifer saturated thickness ranges from 75 m at Shah oil field to 175 m at Bu Hasa. The aquifer's hydraulic conductivity (K), derived from grain-size analysis, is 2.3 to 8.5 m/day. The aquifer transmissivity (T) varies between 200 and 650 m^2/day and its specific capacity (SC) is 40 to 90 m^2/day. The specific yield (Sy), 0.1 to 0.3, indicates a free aquifer, and the hydraulic gradients, 0.01-0.001, reflect the effect of pumping and heterogeneity of the aquifer.

The concentrations of major, minor and trace chemical constituents indicate that the groundwater in the Quaternary Liwa aquifer is fresh (<1,000 mg/l) to saline (>10,000 mg/l). In most parts, the groundwater is hard (TH > 200 mg/l) and not suitable for drinking or domestic purposes. Except bicarbonate ion (HCO_3^-), the concentration of all major ions increases from the center of fresh water mounds outwards in all directions. The contents of nitrate ion (NO_3^-), Fluoride ion (F-), Boron (B), chromium (Cr) and zinc (Zn) are generally above the WHO limit for drinking water. The values of electrical conductivity (EC) and sodium adsorption ratio (SAR) show that the groundwater is harmful to very harmful for irrigation of traditional crops.

The study of the chemistry and stable isotopes (^2H and ^{18}O) of the groundwater in United Arab Emirates indicates the presence of three groundwater-flow systems; local, intermediate and regional groundwater-flow systems (Alsharhan et al., 2001). The flow system encountered in the Bu Hasa and Liwa areas is the regional groundwater-flow system, which is characterized by old water (low ^{14}C activities and low or absence of ^3H). These findings support the proposed past pluvial periods indicated by the radiocarbon dating of lacustrine deposits in the Liwa area (Wood and Imes, 1995).

The stable isotopes (^2H and ^{18}O) are highly enriched in the groundwater of the Quaternary Liwa aquifer, suggesting intensive evaporation prior recharge. The ^2H and ^{18}O values in the groundwater of the Quaternary Liwa aquifer at Liwa and Bu Hasa are identical, suggesting a single common source of the groundwater in both areas. The low ^{14}C activities and lack of ^3H in most samples indicate old groundwater age and absence of present-day recharge.

INTRODUCTION

Preliminary hydrogeological studies on the Western Region of UAE confirmed the presence of local, fresh-water mound between Madinat Zayed and Liwa, and revealed a similar feature at the Bu Hasa area. The authors believe that further groundwater investigations of the sand-dune fields in western UAE may uncover additional fresh-water mounds.

The fast development of the groundwater resources in UAE during the last three decades has lead to sharp aquifer depletion, increase of groundwater salinity, dryness of shallow wells and deterioration of groundwater quality. Shortage of natural water resources is compensated for by expansion in desalination industry and reuse of treated wastewater. Efforts are also focused on construction of groundwater-recharge dams on major wadis in the Eastern Region, application of advanced irrigation technologies and use of recent techniques for groundwater investigations.

The stable (^2H and ^{18}O) and radioactive isotopes (^3H and ^{14}C) are used to identify sources of recharge, recharge mechanisms, sources of increasing groundwater salinity, water pollution and age of groundwater. Together with groundwater models, isotopes can represent powerful tools for groundwater management.

Results of mechanical analysis of six sediment samples from the Liwa area are used to calculate the hydraulic conductivity (K) of the Quaternary Liwa aquifer. The hydrogen-ion concentration (pH), temperature (°C), electrical conductivity (EC), in microsiemens per centimeter (µS/cm) and total dissolved solids (TDS) in milligrams per liter (mg/l) of groundwater samples collected by the authors in 1996 and 1999 form the Madinat Zayed, Liwa and Bu Hasa areas were directly measured in the field using a portable pH (pH model HI-8314) and EC (Myron-L) meters. Samples were analyzed for major ions (cations: Na^+, Ca^{2+} and Mg^{2+}; and anions: HCO_3^-, SO_4^{2-} and Cl^-), minor ions (K^+, CO_3^{2-} and NO_3^-) and trace constituents (Fe, Cu, Zn, Ni, Cr and F^-) in the UAE University Central Laboratories and the Food Control Laboratory of the Abu Dhabi Municipality.

The study area lies in the southern part of the Abu Dhabi Emirate, between Latitudes 22° 45' and 23° 45' N and Longitudes 53° 00' and 54° 30' E, bounded by Habshan oil field in the north, the UAE-Saudi Arabia border in the south, Asab oil field in the east and Bu Hasa oil field in the west (Fig. 1).

Although sand dunes cover 74% of the total area of United Arab Emirates, water-bearing sands are the least-studied aquifer system. Therefore, the objectives of this study are to: investigate the hydraulic properties of the Quaternary Liwa aquifer in western UAE, characterize the groundwater chemistry and evaluate the suitability of groundwater for different uses. The stable and radioisotopes are employed to determine the source and age of the groundwater in the study area.

GEOLOGY

Based on petrophysical studies, Imes et al. (1994) subdivided the stratigraphic column in the Western Region of the Abu Dhabi Emirate, from base to top, into four units; the Dammam Formation, Oligo-Miocene unit, Lower Fars Formation and undifferentiated Quaternary sands (Fig. 2). From the hydrogeologic point of view, the study area can be broadly subdivided into two major stratigraphic division; the Tertiary rocks and Quaternary deposits.

I. Tertiary Rocks

The Eocene Dammam carbonate is the deepest and oldest formation penetrated by shallow water wells in the Liwa and Bu Hasa areas (Hassan and Al Aidarous, 1985), where the formation consists of nummulitic carbonate interbedded with sandstone and mudstone (GeoConsult, 1985). The Dammam Formation represents a major fresh-water aquifer in Saudi Arabia, Qatar and Bahrain (Alsharhan et al., 2001), but in UAE, the Dammam Formation has poor hydraulic properties and contains brackish to saline water.

The Oligo-Miocene clastics unit has an average thickness of 120 m and consists of clay, interbedded with sandstone and limestone. The unit unconformbly overlies the Dammam Formation and is separated from the overlying Lower Fars Formation by an anhydrite bed (GeoConsult, 1985).

The Miocene Lower Fars Formation in the Abu Dhabi Emirate has an average thickness of 200 m at Liwa and 150 m at Bu Hasa. It consists of mudstone, siltstone and marl, interbedded with evaporites and carbonates (Hassan and Al Aidarous, 1985). The Lower Fars Formation acts as confining layer, restricting vertical groundwater flow, because it is composed of siltstone, marl, evaporites and carbonates, with a very low hydraulic conductivity. The top of the formation coincides with a major lithologic change revealed from density and neutron logs (Imes et al., 1994).

II. Quaternary Deposits

The Pleistocene-Holocene sands unconformably overly the Lower Fars Formation in the Liwa and Bu Hasa areas. These sands are fine to medium-grained, clay-free and are composed of quartz, carbonates, evaporites and heavy minerals. Surfacial sabkhas occur between dunes, mainly south of the Liwa Crescent, and are composed of sand and silt. The average thickness of the eolian sand and sabkha unit is 110 m. The Quaternary sands have moderate hydraulic properties and represent the main aquifer in the Liwa and Bu Hasa areas.

HYDROGEOLOGY

The water-bearing units in the Western Region of UAE include: (a) Brine-producing aquifers (Simsima, Um Er' Radhoma and Dammam formations), (b) Waste-disposal aquifer (Miocene clastics) and (c) Domestic water-supply aquifer (Quaternary Liwa sands) (Table 1).

Table 1. The main hydrogeologic units and groundwater uses in the Western Region of UAE (NDC-USGS, 1996).

Hydrogeologic unit	Thickness (m)	Nature	Lithology	Salinity (mg/l)	Importance and use
Liwa aquifer	135	aquifer	eolian sand	3,000	Domestic supply, wash water and fire fighting
Lower Fars confining unit	160	confining unit	evaporites / clastics	5,000	Prevents vertical flow
Miocene Clastics aquifer	100	aquifer	sand	100,000	Receives injected brines
Dammam aquifer	265	aquifer	limestone	70,000	Source of water for injection into reservoirs
Rus confining unit	215	confining unit	anhydrite/ limestone	unknown	none
Um Er' Radhoma aquifer	415	aquifer	limestone	160,000	Source of water for injection into reservoirs
Simsima aquifer	270	aquifer	limestone	230,000	Source of water for injection into reservoirs

The Miocene clastics aquifer at Bu Hasa is used for disposal of oil-wash water and injection of waste bines from petroleum production. Because the Quaternary Liwa aquifer has the lowest salinity in the study area, its water is used for oil-camp domestic supply, irrigation, fir fighting and as dilution water to reduce the salinity of petroleum "wash water". Since the aquifer is shallow, unconfined and composed predominantly of eolian sand, it becomes susceptible to contamination by wastewater moving downward from unlined pits in the desert or through upward movement of poor-quality water from the Miocene aquifer across breaks or "windows" in the overlying confining Fars Formation.

Grain-size analysis of sediment samples collected by the Groundwater Research Project from the Liwa area was performed at the Mineralogy Laboratory, Faculty of Science, UAE University. The cumulative weight of particles was then plotted as a percentage of the total sample weight against grain size in millimeters (Fig. 3). The effective grain size (d_{50}), uniformity coefficient (C_u) and hydraulic conductivity (K) were determined From Figure 3.
In 1958, Taylor indicated that the size of soil particles that is 10% finer by weight governs the hydraulic conductivity (K) of sediments. For fairly uniform sand, Taylor (1948) applied the following equation to determine the hydraulic conductivity (K): $K = C \times (d_{10})^2$, where K is the hydraulic conductivity (m/day), C is a constant, and d_{10} is the size (mm), indicating that 10% of the total sample is finer by weight.

The constant (C) is 850 for sand samples with uniformity coefficient (C_u) less than 5 and effective grain size (d_{10}) between 0.1 and 0.3 m (Taylor, 1958). Because the samples collected from the Liwa area are within the specified C_u and d_{10} ranges, previous equation was applied to calculate the hydraulic conductivities (K). Table 2 illustrates that the calculated hydraulic conductivity for sediment samples from the Quaternary Liwa aquifer varies between 2.31 (m/day) and 8.50 (m/day).

Imes et al. (1994) analyzed the results of pumping test experiments at wells No. GWP 140 and GWP 143, tapping the Quaternary Liwa aquifer at Liwa (Fig. 1). The aquifer transmissivity (T) varies between 200 m^2/day at Well No. GWP 143 and 650 m^2/day at Well No. GWP 140, and the specific capacity (SC) ranges from 40 m^2/day at Well No. GWP 143 and 90 m^2/day at Well No. GWP 140

The saturated thickness of the Quaternary Liwa aquifer within the study area was calculated by subtracting the field-measured depth to groundwater from the depth to the base of the aquifer at each sampled well. Figure 4 shows that the aquifer's saturated thickness ranges from 75 m at the Shah oil field in the south to 175 m at well No. 360 in the Bu Hasa area (Figures 1 and 4).

Groundwater level of the Quaternary Liwa aquifer in the Liwa area varies between a few meters in interdune areas and more than 50 m on the top of sand dunes. At Bu Hasa, depth to the groundwater in the aquifer ranges from 24 m in the northwest and southeast to 52 m in northeast and southwest. The authors measured depth to groundwater in sampled domestic and farm wells at the Liwa and Bu Hasa areas during February 1999. Depths to groundwater, along with ground elevations, were used to construct the hydraulic-head map for the Quaternary Liwa aquifer in the Western Region of UAE (Fig. 5). This map shows the followings:

Table 2. Calculated uniformity coefficient (C_u) and hydraulic conductivity (K) of six sediment samples from the Quaternary Liwa aquifer in the Liwa area.

No.	d_{10}	d_{50}	d_{60}	C_u	K_{Hazen} (m/day)
GWP95	0.078	0.17	0.19	2.44	5.17
GWP96	0.100	0.19	0.23	2.30	8.50
GWP100	0.080	0.18	0.20	2.50	5.44
GWP102	0.085	0.18	0.19	2.24	6.14
GWP105	0.090	0.24	0.30	3.33	6.89
Sand Dune	0.140	0.20	0.23	1.64	2.31

Abbreviation in Tables 2:

d_{10} = grain size that is 10% fine by weight (mm),
d_{50} = grain size that is 50% fine by weight (mm),
d_{60} = grain size that is 60% fine by weight (mm),
C_u = uniformity coefficient [d_{60}/d_{10}], and
K_{hazen} = hydraulic conductivity calculated by Hazen method (m/day).

a. Two groundwater mounds occupy the area between Madinat Zayed and Liwa, and the central part of the Bu Hasa oil field.
b. The general groundwater flow direction in the Bu Hasa area is from south to northwest, in the direction of the Arabian Gulf. In the Liwa area groundwater flows in all directions from the mound centered at Well No. 30, between Madinat Zayed in the north and Mizairaa in the south (Fig. 5).
c. The hydraulic gradient in the Quaternary Liwa aquifer at Bu Hasa is highly variable, ranging from 0.01 in the southwest to 0.001 in the southeast and northwest. In addition to

the effect of pumping, the hydraulic gradient also reflects the heterogeoeous nature of the aquifer.

Figure 5 also indicates that the general groundwater flow from south to northwest agrees with the general groundwater flow pattern in the sandstone aquifer system in UAE (Rizk et al., 1996).

GROUNDWATER CHEMISTRY

The results of chemical analysis for major, minor and trace chemical constituents in groundwater of the Quaternary Liwa aquifer at Liwa and Bu Hasa were used to investigate the effect of geology, hydrogeology and human activities on groundwater chemistry, quality and suitability for different uses.

I. Physical Properties

The hydrogen-ion concentration (pH), electrical conductivity (EC) and total dissolved solids (TDS) were directly measured in the field (Tables 3 and 4). Data of the Groundwater Project, and Shah, Asab and Sahil oil fields are compiled in Table 5.

Table 3. The electrical conductance (EC in µS/cm), total dissolved solids (TDS in mg/l), pH and concentrations of major ions (mg/l) in the groundwater samples collected by the authors from the Quaternary Liwa aquifer in the Liwa area during February 1999.

No.	pH	EC	TDS	Na^+	Ca^{++}	Mg^{++}	K^+	$CO3^{--}$	$HCO3^-$	$SO4^{--}$	Cl^-
8	7.6	18070	13553	2875	759	287	92.5	4.8	98	1722	5312
9	7.4	10240	7680	1582	585	159	57.5	0	49	1316	2550
10	7.4	9320	6990	1546	421	102	55	0	49	1001	2444
11	7.6	8170	5801	1509	174	83	40	3.6	85	2455	2337
12	7.4	5610	3647	1097	62	35	32.5	4.8	307	1263	1381
13	7.5	2270	1453	439	72	10	16	6.3	92	574	482
14	7.6	9060	6614	1725	287	101	35	2.4	92	2242	2196
15	7.6	56690	50683	15916	482	718	400	0	171	11943	19760
16	7.4	11460	8595	2079	584	147	102.5	4.8	165	1682	2550
17	7.7	9430	6884	1438	585	180	85	0	159	1944	1771
18	7.5	8930	6340	1438	585	171	82.5	0	63	2023	1735
19	7.7	15280	11460	2772	728	255	95	3.6	140	2044	4037
20	7.4	12250	9188	2166	616	194	67.5	3.6	123	1531	3187
21	7.3	7380	5092	994	554	198	45	2.4	79	1533	1310
22	7.5	11770	8828	1990	708	242	67.5	1.2	73	2021	2762
23	7.4	8980	6376	1509	708	190	35	0	55	1734	2054
24	7.6	11770	8828	2456	780	217	52.5	0	123	2058	2833
25	7.6	13070	9863	2875	739	227	65	2.4	57	2142	3435
26	7.3	13890	10418	2445	626	282	55	2.4	85	2462	3470
27	7.5	6760	4529	1582	267	95	37.5	4.8	110	1151	1700
28	7.4	12420	9315	2000	603	161	80	0	49	2158	2939
29	7.3	2950	1888	575	144	41	21	0	58	873	496
30	7.8	1260	806	334	21	7	13	7.5	104	186	212

The pH values of the groundwater in the Quaternary Liwa aquifer at Liwa range from 7.3 to 7.8, while the pH of water samples collected from the domestic water-supply wells at Bu Hasa ranged from 6.9 to 7.8 (Fig. 6). The missing pH values of some water samples from the Bu Hasa area were calculated with the relation (Hem, 1985): $[H^+]$ = Log K_2 Log $[HCO_3^{2-}]$/ Log $[HCO_3^-]$.

The EC of the groundwater samples gradually decreases from Habshan towards Liwa, reaching its lowest value (1,260 µS/cm) at Well No. 30, about 20 km north of Liwa. Then, the EC rises again towards Mizairaa at the Liwa Crescent, indicating that the fresh-groundwater mound is centered at Well No. 30, along the Habshan-Liwa road. The EC of the groundwater at the Liwa area varies between 1,260 µS/cm at Mizairaa and 18,070 µS/cm at Habshan, with an average of 9,500 µS/cm. The EC of water samples collected from the domestic water wells at Bu Hasa ranges from 2,700 µS/cm to 8,500 µS/cm, with an average of 4,588 µS/cm.

Table 4. The hydrogen-ion concentration (pH), total dissolved solids (TDS in mg/l) and concentrations of major ions (in mg/l) in the groundwater samples collected by the authors from the Quaternary Liwa aquifer in the Bu Hasa area during February 1999.

No.	Well	pH	TDS	Na^+	Ca^{++}	Mg^{++}	K^+	$CO3^{--}$	$HCO3^-$	$SO4^{--}$	Cl^-
1	WW-02	7.3	3684	988	141	65	45	12	148	635	1639
2	WW-06	7.4	2004	536	71	31	23	14	179	320	817
3	WW-07	7.5	3304	922	73	54	38	38	243	436	1486
4	WW-11	7.6	5026	1113	242	96	49	8	91	900	2506
5	WW-15	7.1	2209	492	63	30	15	7	114	424	1046
6	WW-16	7.4	2893	638	117	47	25	7	105	549	1387
7	WW-17	6.9	1974	450	59	25	17	7	107	388	903
8	WW-18	7.6	3778	989	159	67	42	12	120	726	1646
9	WW-19	7.4	2162	604	75	27	20	7	133	394	889
10	WW-20	7.5	2489	541	90	40	21	10	142	468	1158
11	WW-21	7.7	2821	806	87	37	26	6	107	587	1148
12	WW-22	7.5	2131	479	43	16	12	7	109	395	670
13	WW-23	7.2	1886	440	49	20	16	13	126	337	868
14	CH-03	7.6	5443	853	190	77	35	4	84	1490	2690
15	CH-05	7.6	2415	492	67	27	15	6	109	546	1139
16	CH-06	7.8	6154	1207	248	102	50	6	89	1521	2909
17	CH-07	7.5	2640	654	74	29	20	10	105	520	1213
18	BU-104	6.9*	5829	1696	112	73	50	8	83	18	3797
19	BU-116	8.5*	1806	536	21	10	15	11	32	8	1167
20	BU-121	7.3*	1771	441	4019	5	8	14	158	103	1035
21	BU-173	7.3*	1857	591	6	3	10	14	164	7	1058
22	BU-177	6.2*	2319	663	7	0.2	10	6	84	30	1516
23	BU-181	6.4*	4258	960	137	60	35	7	101	941	1997
24	BU-185	6.1*	1348	343	10	2	9	4	81	134	762
25	BU-329	--	3135	594	214	60	45	--	--	576	1531
26	BU-360	8.2*	2829	802	1	0.1	10	42	314	157	1501
27	BU-377	6.9*	1939	508	11	7	8	2	77	268	1054
28	BU-465	7.4*	2692	704	79	33	21	13	120	494	1214
29	AL DHAFRA	6.7*	2770	647	114	47	34	8	97	553	1250
30	BIN THANI	7.1*	3398	767	1298	486	34	10	101	647	1645

7.4* pH values calculated from the relation $[H^+] = \text{Log } K_2 \text{ Log } [HCO_3^{2-}] / \text{Log } [HCO_3^-]$.

Table 5. Compiled chemistry and water quality data for the Quaternary Liwa aquifer from the Groundwater Project and Shah, Asab and Sahil oil fields.

A. Chemical analysis of groundwater samples from Groundwater Project wells in the Liwa area

No.	Location	pH	TDS	Na^+	Ca^{2+}	Mg^{2+}	K^+	$HCO3^-$	$SO4^-$	Cl^-	$NO3^-$	TH	SAR
94	Lagain	7.5	16815	4200	700	350	145	60	3500	7850	83	1050	52.9
95	Mizairaa	7.5	990	250	65	16	12	110	350	230	20	81	11.1
96	Hameem	7.3	16200	4600	850	350	83	220	2650	7600	75	1200	53.9
98	Al Hamra	7.7	12845	3550	720	265	215	513	2450	5600	53	985	45.8
99	Al Zafrah	7.2	15079	4100	1050	350	98	1525	3800	5600	128	1400	44.2
100	Huwaila	7.2	1402	430	62	12	33	82	330	460	44	74	19.9
101	Asab NW	7.0	9660	2650	600	200	98	18	2250	3800	53	800	37.8
102	Bousadeen	7.3	3424	1100	88	54	25	387	670	1250	57	142	3.8
103	Qafah	7.7	912	325	8.8	3	7	129	175	300	35	11.8	38.2
104	Qafah	7.7	1134	220	120	20	17	51	540	170	6	140	7.4
105	Heea	7.6	3031	990	87	32	44	82	450	1350	41	119	36.7
138	Jarub	--	3295	850	85	2.5	30	107	500	1100	--	87.5	35.5
139	Mussama	7.6	1769	600	20	5.3	19	137	300	500	--	25.3	47.9
140	Khurais	7.6	1056	225	30	6.3	12.6	93	200	200	35	36.3	14.9
142	Huwaila W.	7.8	2013	450	75	30	26	85	300	650	18	105	17.8
143	Bu Hasa S.	7.4	1305	350	15	5.2	12	117	200	350	--	20.2	31.5

B. Chemical analysis of groundwater samples from the Asab oil field in the Liwa area

No.	pH	TDS	Na^+	Ca^{++}	Mg^{++}	$HCO3^-$	$SO4^{--}$	Cl^-	TH	SAR
1	7.5	6,500	1,358	601	156	61	2,058	2,057	757	19.8
4	8.2	9,500	2,489	497	198	68	2,821	3,156	695	38.3
6	8.1	8,950	2,773	325	90	81	1,867	3,688	415	54.7
8	7.9	4,250	1,246	240	75	85	920	1,489	315	28.3
9	8.0	6,850	1,849	325	111	84	1,546	2,571	436	35.8
10	8.0	8,900	2,406	373	123	61	2,197	3,067	496	43.6
11	7.9	6,850	1,934	248	69	112	1,541	2,429	317	43.6
12	7.8	6,400	1,727	293	71	76	1,578	2,181	364	36.2
13	7.6	9,850	2,709	361	132	220	2,561	3,191	493	49.4
15	7.7	18,870	5,232	1,042	419	41	2,800	9,042	1461	55.5
16	8.2	22,750	6,637	1,082	450	454	2,550	11,346	1532	68.9

C. Chemical analysis of groundwater samples from the Sahil oil field in the Liwa area

No.	pH	TDS	Na^+	Ca^{++}	Mg^{++}	$HCO3^-$	$SO4^{--}$	Cl^-	TH	SAR
1	7.6	5,950	1,467	449	94	85	1,606	2,092	543	25.1
2	7.4	13,200	3,606	765	248	73	2,962	5,407	1013	45.7
3	7.6	14,200	3,713	921	280	73	3,276	5,709	1201	43.1
4	7.7	15,530	4,320	1,162	100	61	3,039	6,737	1262	47.9
5	7.8	16,700	4,540	1,422	92	61	3,125	7,446	1514	45.8
6	6.8	18,030	5,032	930	288	81	3,487	7,623	1218	58.1
7	6.9	27,477	8,942	1,042	218	61	3,738	13,474	1260	100.5
8	6.6	13,200	3,318	910	304	73	3,194	5,212	1214	38.4
9	6.7	13,200	3,345	900	306	73	3,187	5,248	1206	38.9
10	7.2	15,079	4,100	1,050	350	51	3,800	5,600	1400	44.2
11	7.6	5,950	1,467	449	94	85	1,606	2,092	543	25.1

D. Chemical analysis of groundwater samples from the Shah oil field in the Liwa area

No.	TDS	Na^+	Ca^{++}	Mg^{++}	$HCO3^-$	$SO4^{--}$	Cl^-	TH	SAR
1	53,460	9,778	1,603	1,021	44	2,800	18,792	2624	78.6
2	36,300	9,552	1,523	924	61	2,700	18,083	2447	79.4
3	33,092	9,887	1,347	836	49	3,600	17,374	2183	87.1
4	47,685	14,778	1,603	1,167	53	4,200	25,883	2770	116.2
5	51,011	15,657	1,779	1,232	42	4,200	28,011	3011	117.9
6	40,120	11,891	1,603	875	40	2,800	21,629	2478	97.9
7	28,754	9,512	1,122	146	63	3,300	14,608	1268	105.7
8	27,177	8,092	1,267	569	57	3,250	18,942	1836	76.9
9	40,820	1,118	1,764	875	49	2,900	20,742	2639	8.9
10	47,630	13,514	2,325	1,459	57	4,250	26,025	3784	90.4
11	26,257	7,883	1,090	622	55	2,850	13,757	1712	78.2

The TDS in the groundwater at Liwa ranges from 806 mg/l north of Mizairaa to 50,683 mg/l in a sabkha area on the right side of the Mizairaa-Ardah road (Well No. 14, Fig. 1). The iso-salinity map of Quaternary Liwa aquifer at Liwa shows that the groundwater salinity increases in all directions away from the center of the fresh-groundwater mound, suggesting that the fresh groundwater body is a localized lens floating on the top of an extensive saline-water body (Fig. 7). At Bu Hasa, iso-salinity data of 1964, 1973, 1976 and 1999 show a gradual increase in groundwater salinity from southeast towards northwest, in the direction of groundwater flow (Al Amari, 1997). Between 1964 and 1985, the groundwater salinity increased in the Dhafrah Camp from 3,500 mg/l to 5,500 mg/l (DF on Figure 1). In the southeastern part of the Bu Hasa area, the groundwater salinity increased from less than 500 mg/l in 1964 to a 1,000 mg/l in 1985. Between 1985 and 1999, the groundwater salinity sharply increased from 1,000 mg/l to 4,500 mg/l, as a result of disposal of oil-field brines in an unlined pit in this area.

Figure 7 shows two fresh water mounds. The large mound has an elliptical shape and occurs between Madinat Zayed and Bu Hasa camp in the north and the Liwa Crescent in the south, extending 120 km in the east-west direction and less than 40 km in the north-south direction. The small mound has an oval shape and exists between Habshan in the northeast and Bu Hasa camp in the southwest.

II. Major Cations

The sequence of cation dominance in the groundwater of the Quaternary Liwa aquifer at the Liwa and Bu Hasa areas has the order: $Na^+ > Ca^{2+} > Mg^{2+} > K^+$. In the Quaternary Liwa aquifer at Liwa, the sodium-ion (Na^+) concentration varies between 334 mg/l and 15,916 mg/l, calcium-ion (Ca^{2+}) content ranges from 21 mg/l to 780 mg/l, magnesium-ion (Mg^{2+}) level varies between 7 mg/l and 282 mg/l and potassium-ion (K^+) concentration ranges from 13 mg/l to 102 mg/l (Fig. 8). The Mizairaa-Hamim side of the Liwa Crescent is characterized by higher values of Mg^{2+} than the Mizairaa-Ardah side a result of heavier groundwater pumping along the former stretch. In general, the concentration of Na^+, Ca^{2+} and Mg^{2+} increases from the center of the mound outwards in all directions.

In the Bu Hasa area, the high Na^+ concentration ranges from 316 mg/l to 1,696 mg/l, Ca^{2+} content varies between 4 mg/l and 248 mg/l, Mg^{2+} content ranges from 0.1 mg/l to 102 mg/l and K^+ concentration ranges from 7 mg/l to 50 mg/l. The high Na^+ concentration in the central part of Bu Hasa is attributed to heavy groundwater pumping for domestic and industrial uses, while the high Na^+ content in the southeastern part of Bu Hasa is a result of disposing highly saline wastewater in an unlined pit.

III. Major Anions

The sequence of anion dominance in the groundwater of the Quaternary Liwa aquifer at the Liwa and Bu Hasa areas has the order: $Cl^- > SO_4^{2-} > HCO_3^- > CO_3^{2-}$. Detected carbonate-ion (CO_3^{2-}) concentration in groundwater of the Quaternary Liwa aquifer at Liwa ranges from 1.2 mg/l to 7.5 mg/l. Bicarbonate-ion (HCO_3^-) value varies between 48 mg/l and 307 mg/l, reaching maximum concentration at the center of the fresh-water mound and decreases outwards in all directions. Sulphate-ion (SO_4^{2-}) content ranges from 186 mg/l to 2,242 mg/l, while the chloride-ion (Cl^-) concentration changes from 212 mg/l to 5,312 mg/l, with a steady increase from the center of the fresh-water mound towards out in all directions (Fig. 9).

In the Bu Hasa area, the Cl^- content in the groundwater of the Quaternary Liwa aquifer ranges from 694 mg/l to 2,909 mg/l. High Cl^- in the southeastern part of Bu Hasa is a result of dumping highly saline wastewater in an unlined pit. The SO_4^{2-} concentration ranges from 7 mg/l to 1521 mg/l, and HCO_3^- level varies between 32 mg/l and 314 mg/l. While the Cl^- and SO_4^{2-} contents increase from south to north, in the direction of groundwater flow, the HCO_3^- concentration decreases in the same direction. The CO_3^{2-} content varies between 7 mg/l and 41 mg/l, being generally low below pH of 8 and increases with increasing pH.

IV. Minor Ions

The nitrate-ion (NO_3^-) is the most common identified contaminant in water (Freeze and Cherry, 1979). The WHO (1984) recommended limits for nitrate in drinking water are 10 mg/l as nitrate-nitrogen (NO_3^--N) and 45 mg/l as nitrate (NO_3^-). The NO_3^- content in groundwater of the Quaternary Liwa aquifer at Bu Hasa varies between 3 mg/l and 19 mg/l, which is below the WHO (1984) recommended limits for drinking water (Fig. 10). The NO_3^- content in groundwater of the Quaternary Liwa aquifer along the Liwa Crescent ranges from 6 to 200 mg/l, with an average of 74 mg/l, which is above the WHO (1984) recommended limits for drinking water. The proximity of most wells to fertilized farmlands accounts for high NO_3^- concentrations in groundwater at this area. However, NO_3^- concentrations in excess of 100 mg/l NO_3^-N are found widely in interstitial water from unsaturated Quaternary sands in northern Senegal (Edmunds and Gaye, 1997). These results provide evidence of a significant built-up in NO_3^- is taking place in the unsaturated zone as a result of natural processes under present day climatic and environmental conditions and is giving rise to high NO_3^- in shallow groundwater. The mechanism of enrichment is likely to be fixation of nitrogen by indigenous or introduced leguminous plants (Edmunds and Gaye, 1997).

V. Trace Constituents

Trace chemical constituents in the groundwater play a critical role in determining the suitability of the groundwater for different uses. Because of the large volume of chemical fertilizers applied to farmlands in the study area, it is important to study their effect of groundwater quality.

Strontium (Sr) concentration in the groundwater of the Quaternary Liwa aquifer ranges from 1 to 35 mg/l at the Liwa Crescent area, and from 9 mg/l to 45 mg/l at Bu Hasa (Fig. 11; Table 6). The WHO has no recommended limit for strontium in drinking water.

Table 6. Concentrations of trace chemical constituents (in mg/l) in the groundwater samples collected by the authors from the Quaternary Liwa aquifer in the Liwa and Bu Hasa areas during February 1999. The abbreviations: Sr = strontium, F^- fluoride ion, Fe = iron, B = Boron, Cr = Chromium and Zn = zinc.

Liwa							Bu Hasa						
No.	Sr	F^-	Fe	B	Cr	Zn	Well No.	Sr	F^-	Fe	B	Cr	Zn
8	--	--	0.057	--	--	0.037	WW2	23.78	3.00	0.03	2.25	0.02	0.01
9	19	--	0.045	3.08	--	0.030	WW7	--	3.79	0.13	2.06	--	0.01
10	0.3	0.05	0.040	--	--	0.022	WW19	12.9	2.94	0.07	1.75	0.03	0.01
11	4.5	--	0.033	1.21	--	0.017	WW21	10.77	2.98	0.10	2.13	0.02	--
12	2.6	--	0.056	0.80	--	0.055	WW6	--	2.69	0.03	1.75	0.03	0.02
13	2.0	3.0	0.027	1.05	0.140	0.018	WW18	21.1	2.43	0.11	2.31	--	0.02
14	32	3.0	0.028	1.60	0.170	0.024	WW11	30.52	3.14	0.08	2.00	0.02	0.02
15	19	6.2	0.241	1.05	0.140	0.050	WW17	10.36	2.99	0.03	1.50	--	0.01
16	18	4.2	0.056	0.95	0.120	0.040	WW16	--	2.89	0.08	1.13	0.02	0.01
17	14	--	0.044	2.11	--	0.019	WW20	17.85	2.52	0.07	1.56	0.02	0.01
18	16	--	0.051	3.92	--	0.039	WW15	19.01	2.99	0.07	1.25	0.02	--
19	21	4.2	0.066	1.25	0.185	0.027	WW23	13.31	3.04	0.11	0.94	--	--
20	20	6.0	0.047	1.41	0.175	0.023	WW22	--	3.00	0.07	1.00	--	0.02
21	20	4.8	0.036	1.51	0.185	0.175	CH7	9.36	2.57	0.07	1.00	--	0.01
22	23	3.0	0.059	1.05	0.120	0.088	CH6	--	2.72	0.02	1.31	--	0.01
23	25	2.1	0.051	1.10	0.130	0.045	CH5	10.36	2.46	0.05	0.56	--	0.01
24	16	--	0.058	2.97	--	0.077	CH3	22.79	3.35	0.15	0.88	--	--
25	9	--	0.045	1.32	--	0.037	BU-377	--	3.21	0.07	0.81	--	0.01
26	11	1.9	0.068	1.15	0.150	0.027	BU-173	--	3.33	0.23	0.81	--	--
27	21	--	0.030	1.72	--	0.023	BU-465	--	3.59	0.03	1.06	0.02	--
28	28	--	0.049	3.07	--	0.030	BU-181	--	3.12	0.18	0.94	0.05	--
29	20	4.8	0.033	1.50	0.185	0.416	BU-177	--	3.47	0.10	0.56	--	0.01
30	21	--	0.031	0.87	--	0.045	BU-329	--	0.54	--	1.06	--	0.16
31	--	--	0.009	--	--	0.346	Al Dhafra	21.1	0.38	0.13	0.81	--	0.01
32	--	--	--	--	--	--	Bin Thani	45.11	1.92	0.07	0.63	0.02	0.02
33	--	--	0.023	--	--	0.019	BU-185	--	2.57	0.18	0.63	--	0.01
34	--	--	0.029	--	--	0.011	BU-360	--	2.17	0.13	1.44	0.02	0.01
35	--	--	0.009	--	--	0.014	BU-104	--	1.32	0.07	0.69	--	0.01
46	--	--	0.003	--	--	0.020	BU-121	--	2.64	0.05	1.00	--	0.01
47	--	--	0.067	--	--	0.030	BU-336	--	1.40	0.13	0.69	0.06	--
48	--	--	0.032	--	--	0.012	BU-116	--	0.73	3.07	0.69	0.01	0.01

Fluoride-ion (F^-) concentration in the groundwater of the Quaternary Liwa aquifer varies between 0.6 mg/l and 6.2 mg/l at Liwa. The WHO recommended limit for fluoride in drinking water is 1.5 mg/l. The F^- causes: (a) mottling of teeth at concentrations higher 1.5 mg/l, (b) skeletal fluorosis between 3 mg/l and 6 mg/l and (c) crippling fluorosis at concentrations above 10 mg/l (Imes et al., 1994). The F^- content in most groundwater samples form the Liwa area exceeds the WHO recommended limit for drinking water, whereas its concentration in groundwater of the Quaternary Liwa aquifer at Bu Hasa varies between 0.7 mg/l and 3.6 mg/l.

The total iron (Fe) concentration in the groundwater of the Quaternary Liwa aquifer at Liwa ranges from 0.03 to 0.24 mg/l, while the Fe content in the groundwater at Bu Hasa varies between 0.03 and 3.07 mg/l, which are all below the WHO has no recommended limit for Bromide in drinking water (0.3 mg/l), except for Well No. Bu-116 at the Bu Hasa area. The low Fe content is attributed to the free nature of the aquifer in the study area.

Boron (B) level in the groundwater of the Quaternary Liwa aquifer at Liwa area ranges from 0.70 to 6.36 mg/l. Boron content in all sampled wells in the Liwa area exceeds the WHO recommended limit of 0.3 mg/l. High boron concentration is toxic to some types of vegetation. Based on measured boron concentrations and Table 7, Imes et al. (1994) concluded that the groundwater water at Liwa is unsuitable for sensitive crops, permissible to doubtful for semi-tolerant crops and good for tolerant crops. Boron content in water samples collected from the Quaternary Liwa aquifer at Bu Hasa varies between 0.60 mg/l and 2.25 mg/l. The groundwater in the western and northeastern parts of Bu Hasa is good for sensitive crops, whereas water in the rest of Bu Hasa field is good for semi-tolerant and tolerant crops.

Table 7. Rating of irrigation water for various crops on the basis of boron concentration, in milligrams per liter, in the water (Hem, 1985).

Water class	Sensitive crops	Semi-tolerant crops	Tolerant crops
Excellent	< 0.33	< 0.67	< 1.00
Good	0.33 - 0.67	0.67 - 1.33	1.00 - 2.00
Permissible	0.67 - 1.00	1.33 - 2.00	2.00 - 3.00
Doubtful	1.00 - 1.25	2.00 - 2.50	3.00 - 3.75
Unsuitable	> 1.25	> 2.50	> 3.75

The WHO recommended limit for chromium (Cr) in drinking water is 0.05 mg/l. Measured chromium concentrations in the groundwater of the Quaternary Liwa aquifer are 0.09 mg/l to 0.46 mg/l at Liwa, and 0.01 mg/l to 0.06 mg/l at Bu Hasa. This shows that the chromium contents in all the groundwater samples from the Liwa area are above the WHO recommended limit for drinking water, while the chromium contents in almost all groundwater samples from the Bu Hasa area are within the WHO recommended limit for drinking water.

The WHO recommended limit for zinc (Zn) in drinking water is 0.05 mg/l. Concentrations of zinc in the groundwater of the Quaternary Liwa aquifer are 0.04 mg/l to 0.72 mg/l at Liwa, and 0.3 mg/l to 1.3 mg/l at Bu Hasa. The zinc concentration in some groundwater samples from the Liwa area is within the WHO recommended limit for drinking water, while zinc content in all groundwater samples from the Bu Hasa area is above the WHO recommended limit for drinking water.

GROUNDWATER EVALUATION

Water applied for domestic purposes has certain standard specifications as regards to its physical, chemical and biological properties. The World Health Organization provides and updates guideline values for concentration of dissolved chemical species in drinking water. These standards are intended primarily to protect human health (McCutcheon, 1993).

In addition to the following discussion, the previous section on water chemistry illustrated range of concentrations of major, minor and trace chemical constituents in the groundwater of the Quaternary Liwa aquifer at Liwa and Bu Hasa. The consistency of these ranges with the WHO (1984) recommended limits determine the suitability of water for different purposes.

The groundwater mounds in the Quaternary Liwa aquifer are characterized by relatively good-quality water. As far as salinity is concerned, the groundwater of these mounds is suitable for domestic purposes. However, careful and detailed water-quality parameters have to be evaluated if wells tapping these mounds are to be used for drinking purposes. The WHO (1984) and Gulf Cooperation Council (GCC) standards for dissolved, inorganic chemicals in drinking water are listed in Table 8.

The calculated total hardness of the groundwater in the Quaternary Liwa aquifer ranges from 28 mg/l to 1200 mg/l at Liwa and form 1 mg/l to 407 mg/l at Bu Hasa (Table 10; Fig. 12), indicating that groundwater in both areas vary from soft (<100 mg/l) to very hard (>200 mg/l). However, the groundwater in the Liwa area is mostly very hard, while the groundwater at Bu Hasa cover the whole range of hardness form soft to very hard (Table 9).

Table 8. Comparison of quality parameters for groundwater from the Quaternary Liwa aquifer in the Liwa and Bu Hasa areas, versus the WHO and Gulf Cooperation Council (GCC standards) for drinking water.

Parameter	Liwa	Bu Hasa			WHO	GCC
	Ave.	Max.	Min.	Ave.	Guideline Value	Maxi. Level
pH	7.7	7.8	6.9	7.5	6.5 - 8.5	6.5 - 8.5
Temp.	--	35.0	30.4	32.8	--	--
TDS	3804	6154	1210	2893	1000	100 - 1000
EC	2733	8500	3100	4588	1400	160 - 1600
Hardness	--	983	182	383	500	500
Ca	233	248	1	87	75 - 200	200.0
Mg	76	102.4	0.1	36.4	--	150.0
Na	862	1696	317	702	200.0	200.0
K	78	50	7	25	--	--
CO3	--	42	0	10	--	--
HCO3	106	314	0	117	--	--
Cl	1287	3797	670	1430	250.0	250.0
NO3	103	19	0	9	10.0	10.0
SO4	910	1521	7	472	200 - 400	400.0
SiO2	--	13.6	0.3	9.3	--	--
F	3.4	3.8	0.4	2.6	1.5	0.6 - 1.7
Fe	--	3.07	0.02	0.19	0.30 - 1.00	0.30
B	3.52	2.31	0.56	1.20	--	--
Zn	0.38	0.16	0.00	0.01	5.00	5.00
Ni	--	0.21	0.00	0.03	--	--
Cu	--	0.15	0.00	0.03	1.00 - 1.50	1.00
Mn	--	4.31	0.00	0.19	0.10	0.10
Cr	--	0.06	0.00	0.01	0.05	0.05
Li	1.01	--	--	--	--	--
Sr	18	45	9	18	--	--
Ba	0.08	0.05	0.00	0.00	--	--
Pb	--	0.00	0.00	0.00	0.05	0.05
Se	--	--	--	--	0.01	0.01

For evaluating the suitability of the groundwater in the Quaternary Liwa aquifer at Liwa and Bu Hasa for agriculture, the sodium adsorption ratio (SAR) is usually used. The SAR = Na / $((Ca + Mg)/2)^{0.5}$, where concentrations of Na^+, Mg^{2+} and Ca^{2+} are expressed in meq/l. Calculated SAR values for the groundwater in the Quaternary Liwa aquifer varies between 9.2 and 107.4 at Liwa, and from 2.7 and 309.2 at Bu Hasa (Fig. 13). The SAR values of groundwater at Liwa are widely variable, and so are the harmful effects this water could cause when used for irrigating traditional crops. At Bu Hasa, the groundwater in the Quaternary Liwa aquifer mostly has high SAR values and its use as irrigation water can be harmful to very harmful for traditional crops.

The U. S. Salinity Laboratory Staff diagram (1954), for evaluating the suitability of water for irrigation purposes, shows that the groundwater of the Quaternary Liwa aquifer in the Liwa area is unsuitable for irrigation purposes and mostly plot outside the range of the graph. Despite their relatively lower SAR, groundwater from Bu Hasa is also unsuitable for agricultural uses (Figures 14a and 14c).

Table 9. Measured NO_3^- concentration and calculated values of total hardness (TH) and sodium adsorption ratio (SAR), in mg/l, for groundwater samples collected by the authors from the Quaternary Liwa aquifer at the Liwa and Bu Hasa areas during February 1999. The stable isotopes ^2H(‰) and ^{18}O(‰) were analyzed at the at the International Atomic Energy Agency (IAEA) central laboratories in Vienna, Austria.

Liwa						Bu Hasa					
No.	NO_3^-	TH	SAR	^{18}O(‰)	^{2}H(‰)	Well No.	NO_3^-	TH	SAR	^{18}O(‰)	^{2}H(‰)
8	383.6	1046	22.6	2.53	-16.7	WW-02	6.69	205	28.1	--	--
9	164.2	744	15.0	1.96	-2.7	WW-06	8.46	102	21.6	2.86	1.3
10	161.1	523	17.5	1.85	-3.1	WW-07	9.88	128	33.8	--	--
11	--	257	23.6	1.92	-2.1	WW-11	12.28	337	24.6	2.65	-1.4
12	--	97	27.5	1.94	-1.8	WW-15	8.72	93	20.8	--	--
13	55.4	82	12.9	2.03	-2.4	WW-16	13.19	164	20.2	--	--
14	214.8	388	22.3	2.62	0.1	WW-17	16.71	84	20.0	--	--
15	210.1	1200	107.4	10.51	43.1	WW-18	13.02	226	26.7	--	--
16	183.7	731	19.9	2.70	-0.4	WW-19	14.13	102	24.2	--	--
17	585.9	765	13.3	2.70	1.0	WW-20	14.73	131	19.3	--	--
18	--	756	13.4	2.88	2.6	WW-21	12.73	124	29.4	--	--
19	318.7	983	22.5	2.92	1.7	WW-22	11.71	59	25.2	--	--
20	476.1	810	19.5	2.71	-2.6	WW-23	9.62	69	21.5		
21	22.1	752	9.2	2.78	6.3	CH-03	12.91	267	21.2	2.44	-3.6
22	357.6	950	16.5	2.64	3.5	CH-05	19.13	94	20.6	2.11	-2.7
23	--	898	22.6	2.73	3.3	CH-06	11.81	350	26.2	--	--
24	404.4	997	15.0	2.89	4.0	CH-07	17.55	103	26.1	--	--
25	268.5	966	17.5	2.93	4.7	BU-104	--	174	52.7	4.27	8.7
26	263.8	908	23.6	2.90	0.2	BU-116	2.73	31	39.4	--	--
27	260.2	362	27.5	2.47	1.4	BU-121	--	407	2.7	2.31	-0.1
28	229.9	764	12.9	2.81	2.8	BU-173	--	8	85.3	1.73	-4.1
29	214.8	185	22.3	2.52	5.2	BU-177	--	7	100.7	1.89	-3.3
30	64.6	28	107.4	2.86	6.2	BU-181	15.09	196	27.9	2.31	-1.8
31	--	454	19.9	-1.37	-7.1	BU-185	--	12	40.2	--	--
32	--	83	13.3	-1.68	-6.5	BU-329	7.20	28	14.4	--	--
33	--	144	13.4	-1.64	-3.7	BU-360	--	1	309.2	6	8.5
34	--	122	22.5	-0.99	-2.6	BU-377	--	18	49.7		
35	--	199	19.5	-1.23	-0.9	BU-465	8.99	112	27.0	2.26	0
46	--	154	9.2	-2.11	-6.7	AL DHAFRA	17.07	161	20.7	--	--
47	--	1151	16.5	-0.90	-23.1	BIN THANI	16.09	177	23.3	--	--

Trilinear Piper (1944) plot shows that the groundwater samples from the Quaternary aquifer Liwa at the Liwa area belong to the sodium chloride water type (Fig. 14b). The appearance of most of the groundwater samples from Bu Hasa in the upper portion of the central diamond suggests that the calcium and magnesium chloride and sulfate water types are dominant. A few water samples belong to the Na and K-carbonate and bicarbonate types.

ISOTOPE HYDROLOGY

The study of the chemistry and stable isotopes (^2H and ^{18}O) of the groundwater in United Arab Emirates indicates the presence of three groundwater-flow systems; local, intermediate and regional groundwater-flow systems (Alsharhan et al., 2001). The flow system encountered in the Bu Hasa and Liwa areas is the regional groundwater-flow system, which is characterized by old water (low ^{14}C activities and low or absence of ^3H). These findings support the proposed past pluvial periods indicated by the radiocarbon dating of lacustrine deposits in the Liwa area (Wood and Imes, 1994).

The stable isotopes in groundwater of the Quaternary Liwa aquifer at Liwa and Bu Hasa plot far from the Global Metroric Water Line (GMWL), suggesting isotopes enrichment before and/or during groundwater recharge. The ^2H and ^{18}O values in several water samples from the Quaternary Liwa aquifer in the Liwa and Bu Hasa areas are identical, suggesting a single common source of the groundwater in both areas (Fig. 15).

The tritium values in the groundwater of the Quaternary Liwa aquifer in the Liwa and Bu Hasa areas are low, 0.1 to 3.4 Tritium Units (TU) with an average of 0.6, indicating old-age groundwater but do not rule out the possibility of recharge during relatively heavy rainstorms which occasionally may affect this extremely arid region. Despite old age, the groundwater in the Quaternary Liwa aquifer has low chloride ion and total dissolved solids contents as a result of the clean nature of aquifer-forming sands.

CONCLUSIONS

The hydrogeological investigation of the Quaternary sands in Western United Arab Emirates by the authors during 1996-1999 period revealed the presence of a local, fresh water aquifer in the Bu Hasa area, and confirmed the presence of a similar feature between Liwa and Madinat Zayed. Because of the striking similarity of hydraulic properties, chemistry and natural isotopes of the groundwater at Liwa and Bu Hasa, the aquifer in both areas is dealt with as a single aquifer named the"Quaternary Liwa aquifer".

The results of hydrogeological, hydrogeochemical and isotopic measurements and analyses suggest that the two fresh water mounds encountered in the study area represent relics of an old large aquifer originated during Holocene pluvial period, 5,000 to7000 radiocarbon years PB (Wood and Imes, 1995). The first mound is large, elliptical and occurs between Madinat Zayed and Bu Hasa camp in the north and the Liwa Crescent in the south. It extends 120 km in the east-west direction and 40 km in the north-south trend. The second mound is small, oval mound exists between Habshan in the northeast and Bu Hasa camp in the southwest. This mound has an average diameter of 40 km.

The saturated thickness of the Quaternary Liwa aquifer within the study area was calculated by subtracting the depth to groundwater from the base of the aquifer at each sampled well. The aquifer thickness ranges from 75 m at the Shah oil field in the south to 175 m at Well No. 360 in the Bu Hasa area. The groundwater depth in the Liwa area varies between a few meters in interdune areas and more than 50 m on the top of sand dunes, and in the Hasa, depth to the groundwater ranges from 24 m in the northwest and southeast to 52 m in northeast and southwest. The hydraulic conductivity (K), derived from grain-size analysis of six sediment samples derived from boreholes tapping the aquifer ranges from 2.3 m/day to 8.5 m/day. The aquifer transmissivity (T), obtained from pumping-test experiments, varies between 200 m^2/day and 650 m^2/day and the specific capacity (SC) is 40 m^2/day to 90 m^2/day. The specific yield (Sy), 0.1 to 0.3, indicates a free aquifer, and the hydraulic gradients, 0.01-0.001, reflect the effect of pumping and heterogeneous nature of the aquifer.

The concentrations of major, minor and trace chemical constituents indicate that the groundwater in the Quaternary Liwa aquifer is fresh (<1,000 mg/l) to saline (>10,000 mg/l). In most parts, the groundwater is hard and not suitable for drinking or domestic purposes. Except bicarbonate ion (HCO_3^-), the concentration of major ions increases from the center of the fresh water mounds outwards in all directions. The sequence of cations dominance is $Na^+ < Ca^{2+} < Mg^{2+}$, and the sequence of anions dominance is $Cl^- < SO_4^{2-} < HCO_3^-$, suggesting old groundwater. Trilinear plot also shows that NaCl is the dominant water type in the Quaternary Liwa aquifer within the study area. The contents of nitrate ion (NO_3^-), Fluoride ion (F-), Boron (B), chromium (Cr) and zinc (Zn) are generally above the WHO limit for drinking water. The values of electrical conductivity (EC) and sodium adsorption ratio (SAR) show that the groundwater is harmful to very harmful for irrigation of traditional crops.

The stable isotopes (^2H and ^{18}O) are highly enriched in the groundwater of the Quaternary Liwa aquifer, suggesting intensive evaporation prior recharge. The ^2H and ^{18}O values in the groundwater of the Quaternary Liwa aquifer at Liwa and Bu Hasa are identical, suggesting a single common source of the groundwater in both areas. The low ^{14}C activities and lack of ^3H in most samples indicate old groundwater age and absence of present-day recharge. However, ^3H values of 3.4 Tritium Units (TU), do not rule out the possibility of recharge during relatively heavy rainstorms which occasionally may affect this extremely arid region. Despite old age, the groundwater in the Quaternary Liwa aquifer has low Cl^- and TDS contents as a result of the clean nature of aquifer-forming sands.

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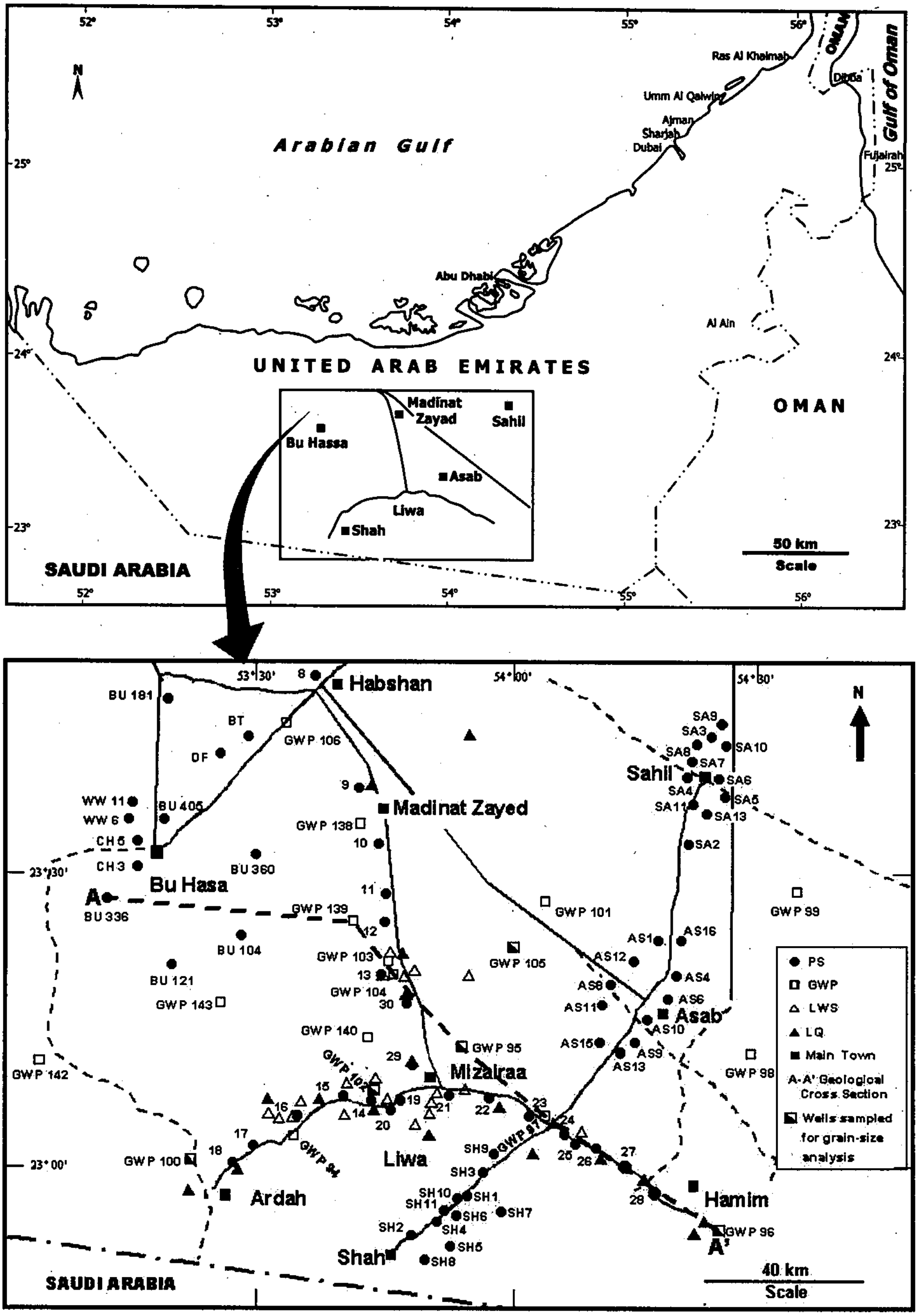

Figure 1. Location map of the study areas in the United Arab Emirates. Location water wells sampled in the present study (●PS), wells of the Ground Water Project (□ GWP), Water and Electricity Department wells (△LWS), wells of water quality monitoring (▲LQ), and wells sampled for gain-size analysis (◪).

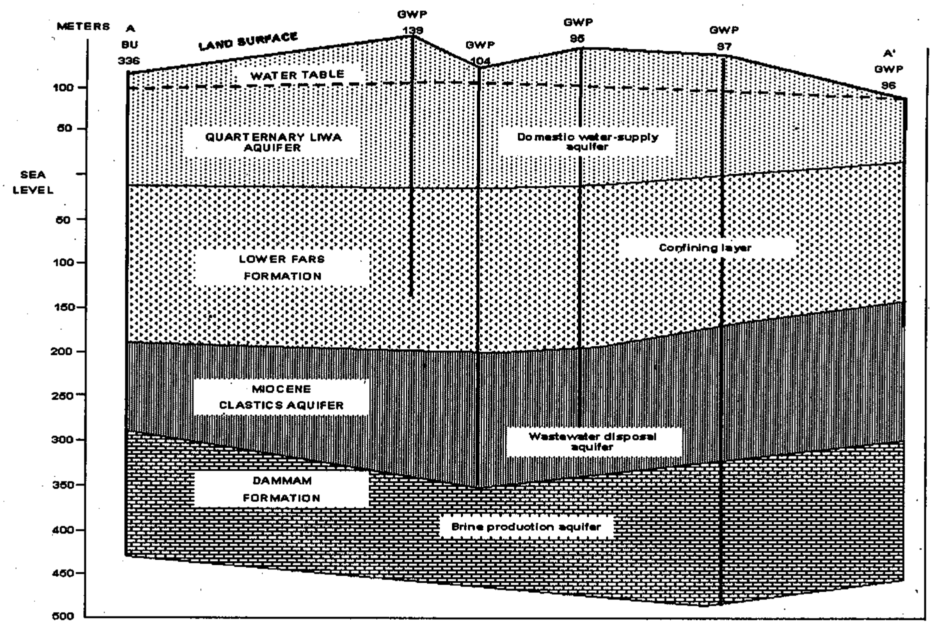

Figure 2. Simplified geological cross-section showing the main water-bearing units in the Liwa and Bu Hasa areas (modified from Imes et el., 1994.

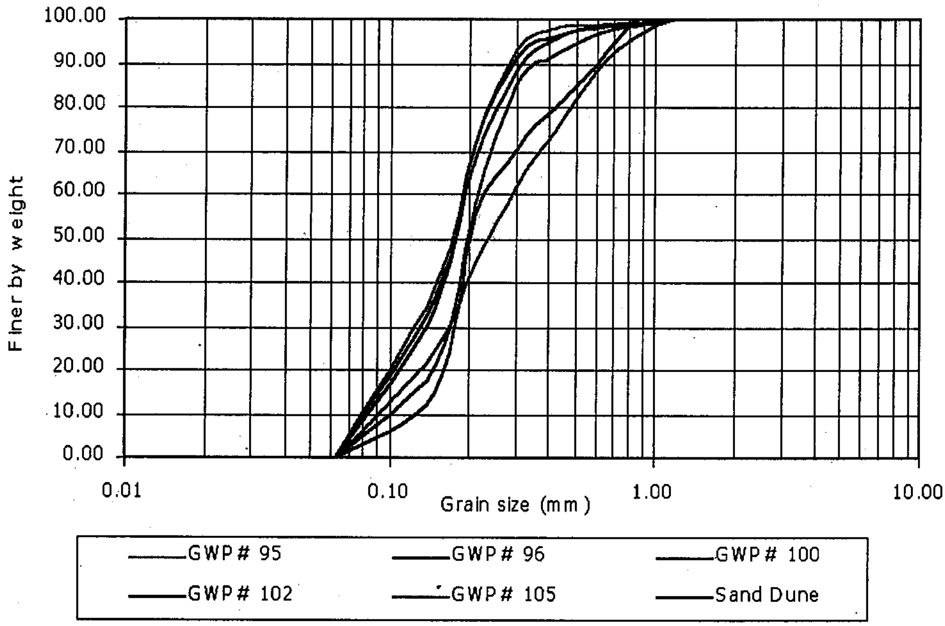

Figure 3. Results of grain-size analysis for six sediment samples from the Quaternary Liwa aquifer in the Liwa area.

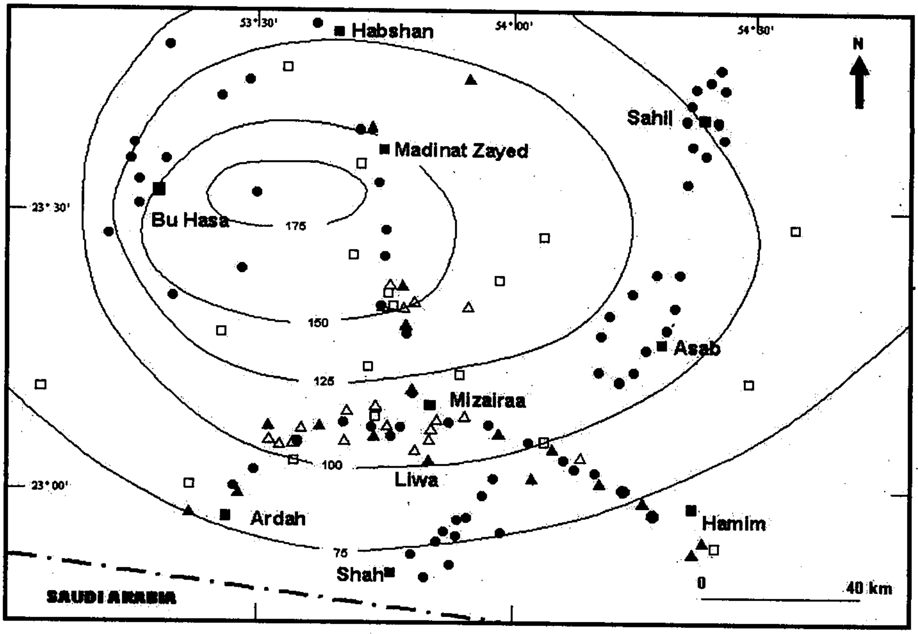

Figure 4. Iso-saturated thickness contour map of the Quaternary Liwa aquifer, in meters, in February 1999.

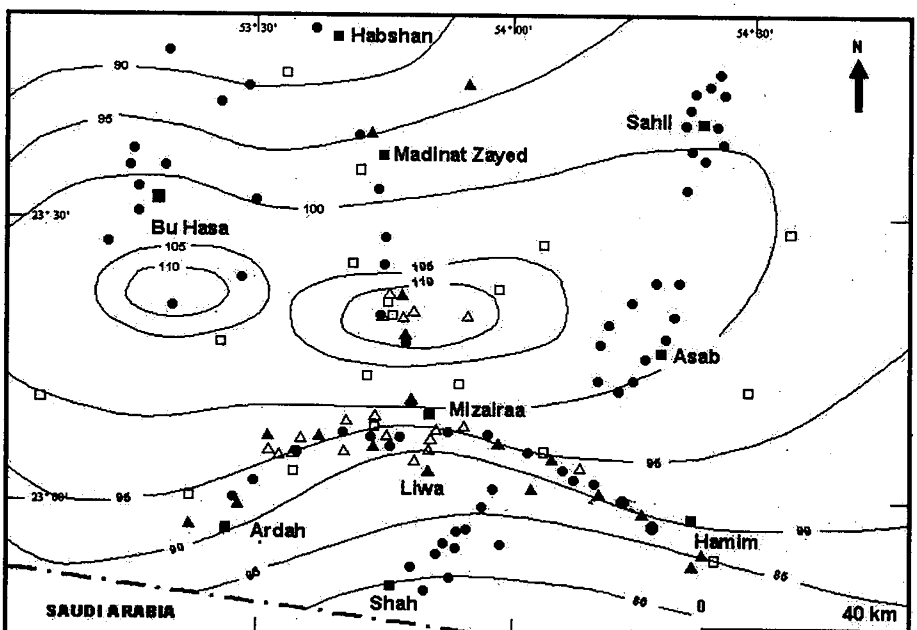

Figure 5. Hydraulic head contour map of the Quaternary Liwa aquifer, in meters above mean sea level, in February 1999.

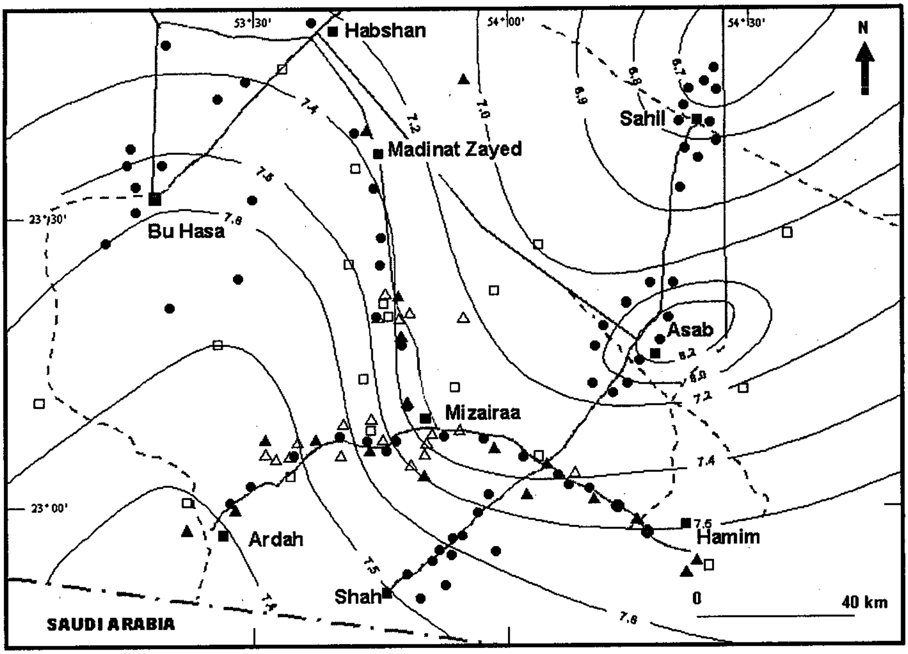

Figure 6. Iso-pH contour map of the groundwater in the Quaternary Liwa aquifer during February 1999.

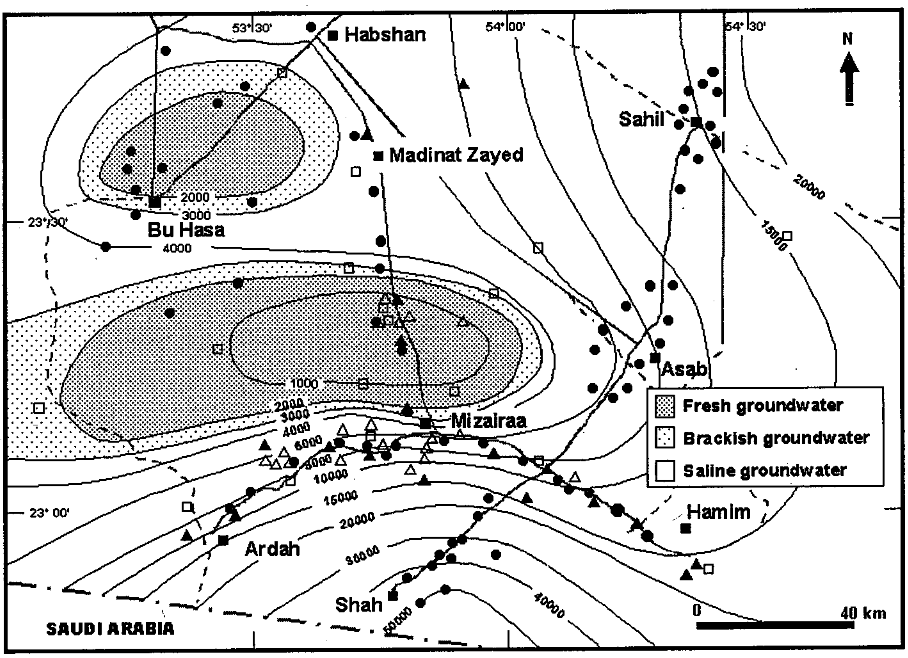

Figure 7. Iso-salinity contour map of the groundwater in the Quaternary Liwa aquifer in milligram per liter during February 1999.

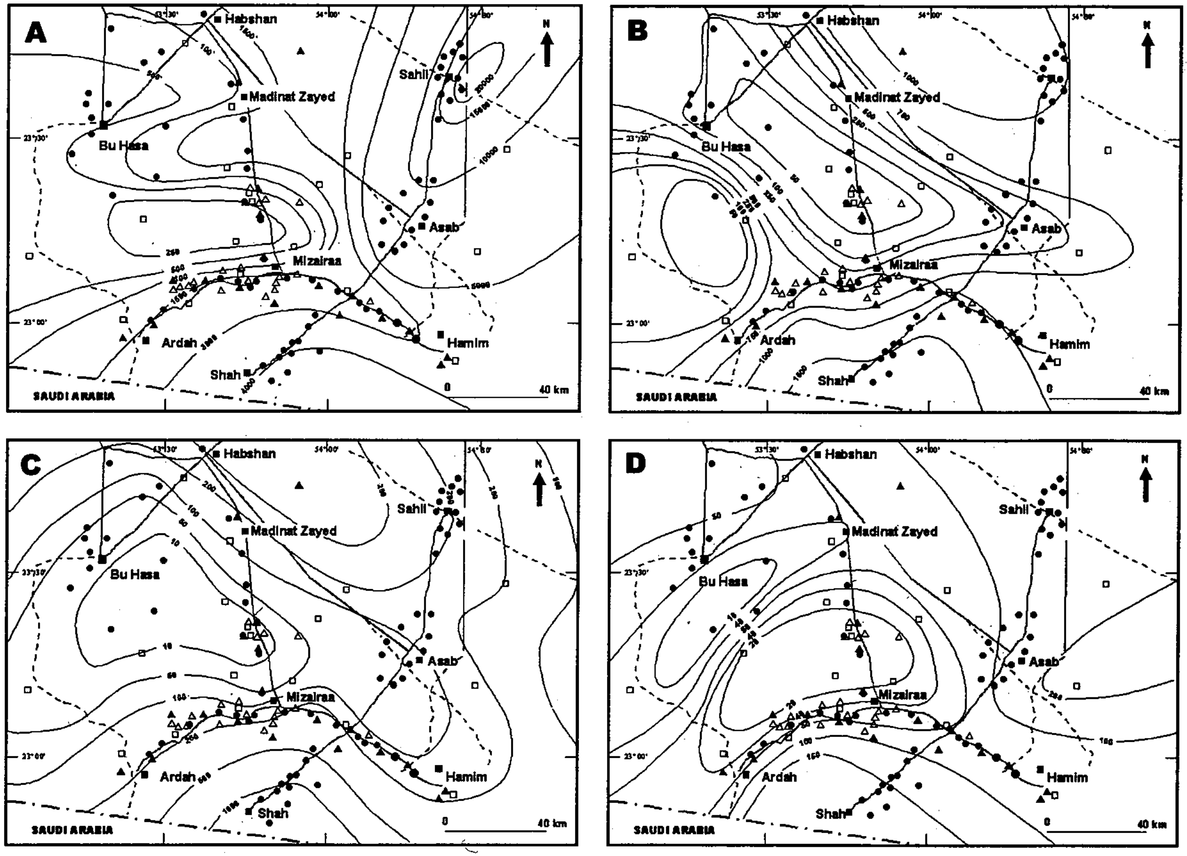

Figure 8. Iso-concentration contour map of major cations in the groundwater of the Quaternary Liwa aquifer, in milligrams per litter, during February 1999. Sodium ion (A), Calcium ion (B), Magnesium ion (C) and Potassium ion (D).

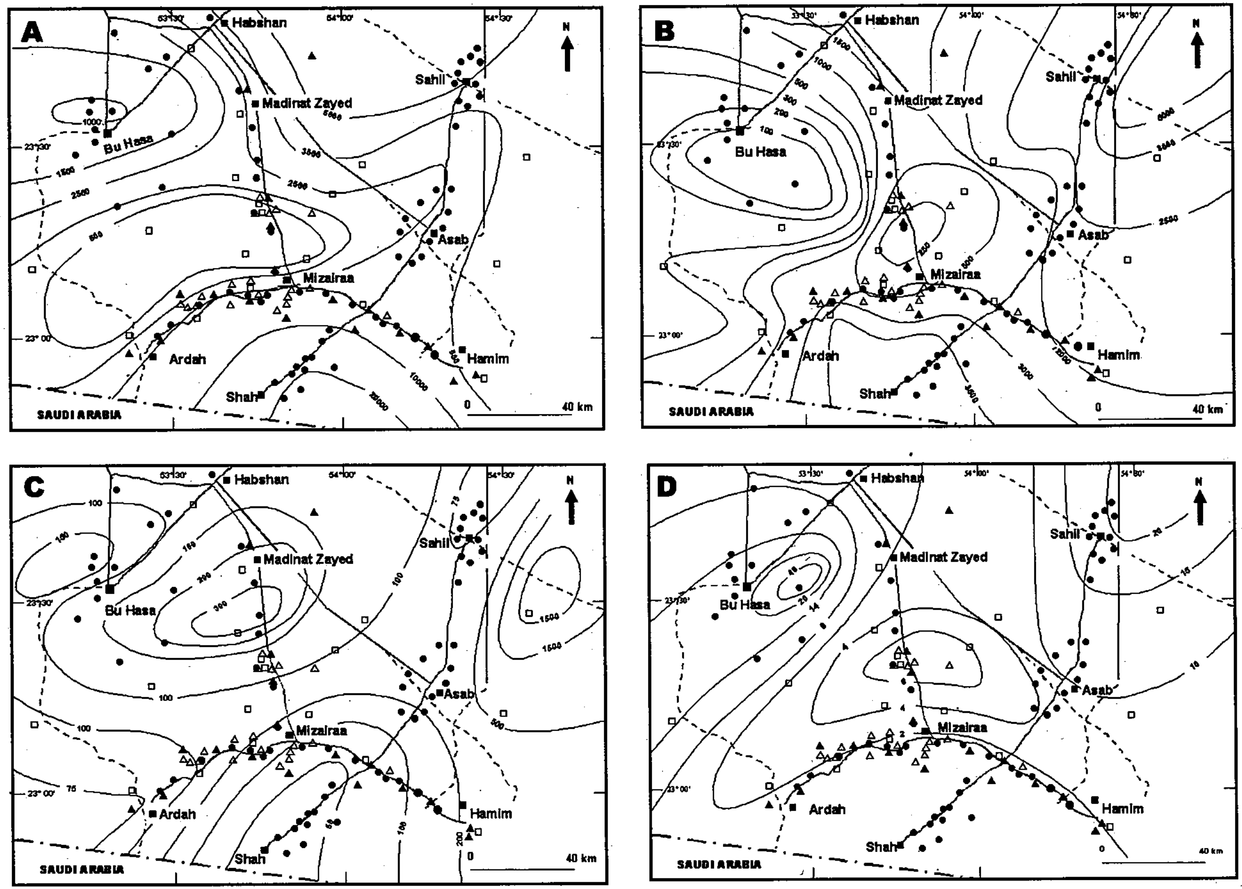

Figure 9. Iso-concentration contour map of major anions in the groundwater of the Quaternary Liwa aquifer, in milligrams per litter, during February 1999. Chloride ion (A), Sulphate ion (B), Bicarbonate ion (C) and Carbonate ion (D).

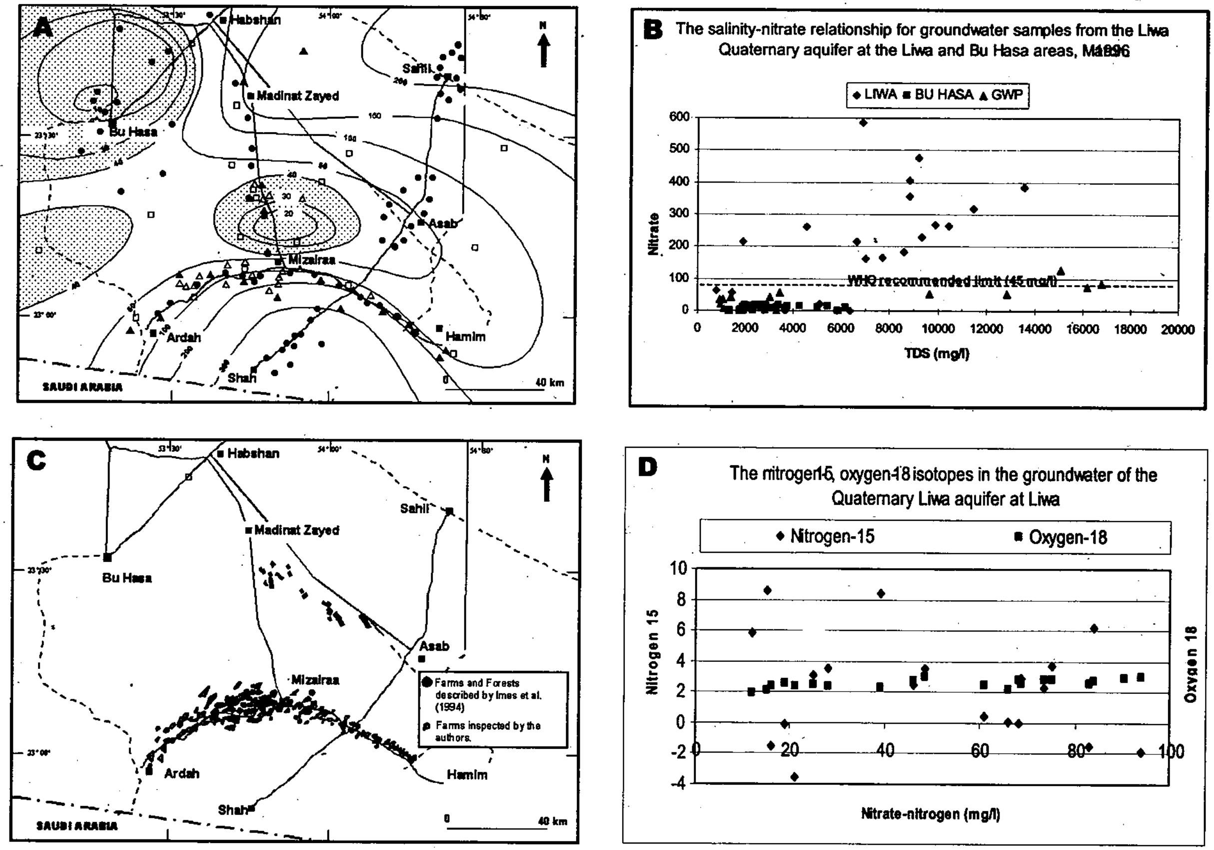

Figure 10. Relationship of the nitrate concentration in the groundwater of the Quaternary Liwa aquifer (A) to the salinity (B), distribution of farms and forests (C) and nitrogen-15 and oxygen-18 isotopes (D). The ^{15}N data is the subject of further investigation.

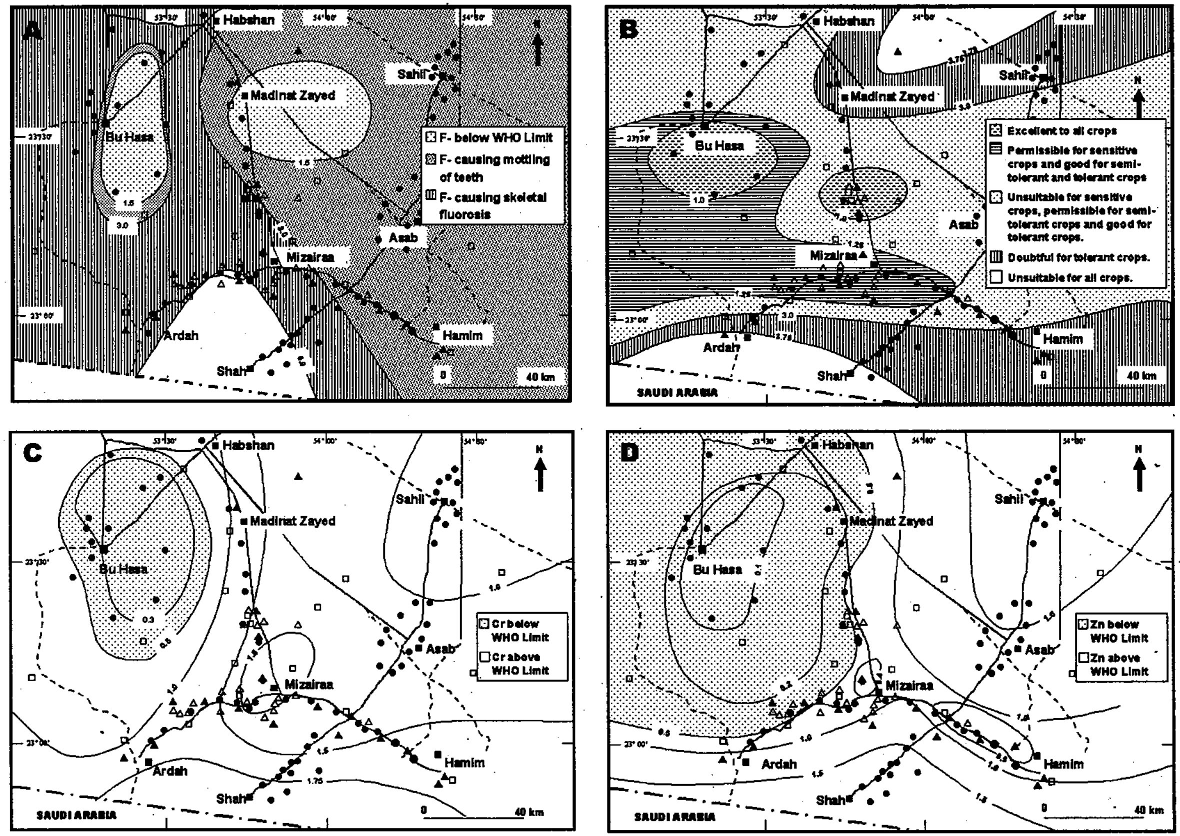

Figure 11. Interpretation of Iso-concentration (mg/l) contour maps of selected trace elements in the groundwater of the Quaternary Liwa aquifer in the Liwa and Bu Hasa areas, February 1999. Fluoride ion (A), Boron (B), Chromium (C) and Zinc (D).

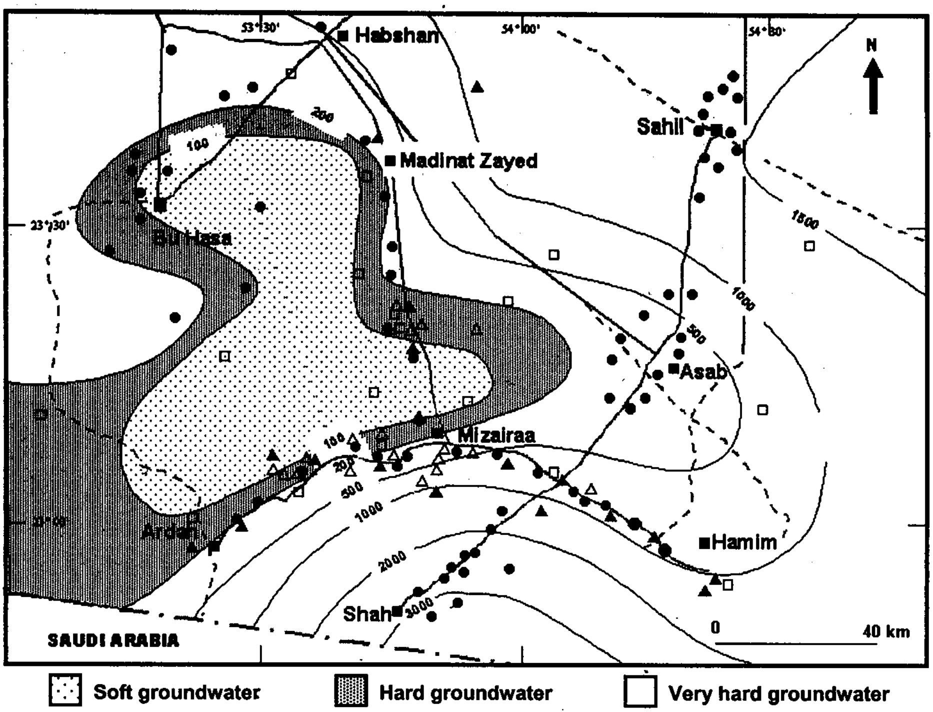

Figure 12. Classification of the groundwater in the Quaternary Liwa aquifer according to total hardness (TH).

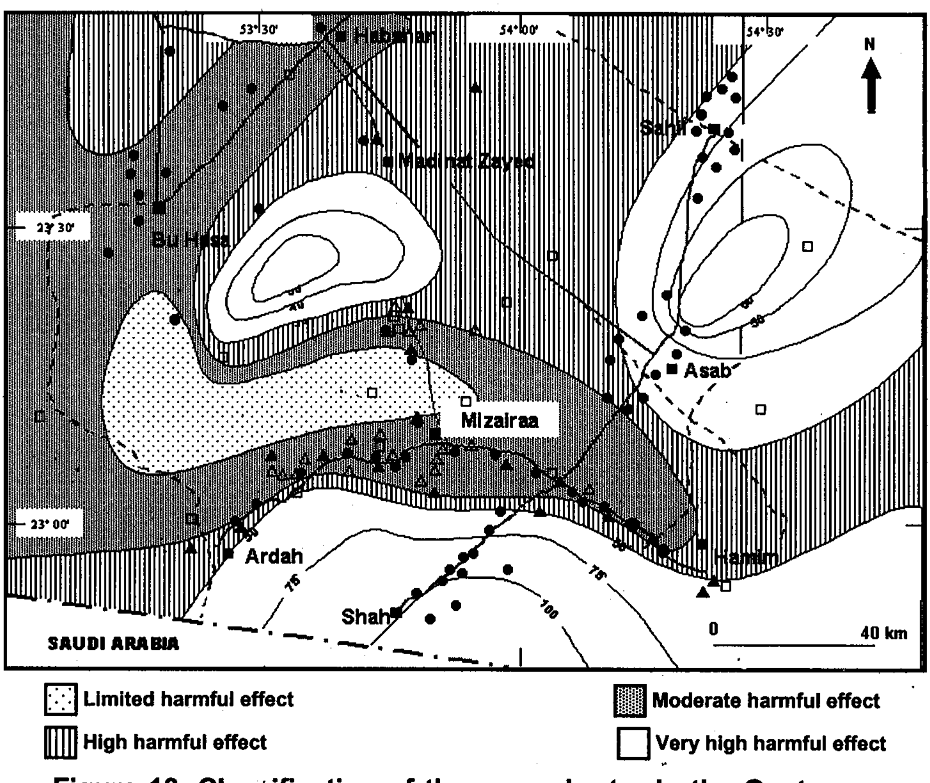

Figure 13. Classification of the groundwater in the Quaternary Liwa aquifer according to the sodium adsorption ratio (SAR).

A

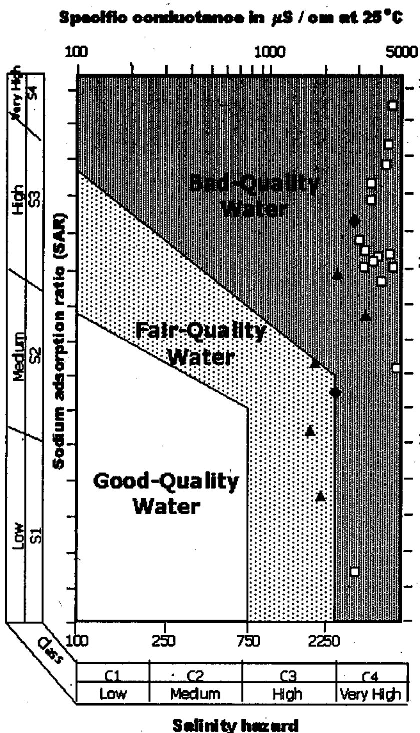

Figure 14A. Classification of irrigation water in the Groundwater Project wells (▲), liwa wells (◆) and Bu Hasa wells (□), tapping the Quaternary Liwa aquifer, February 1999.

B

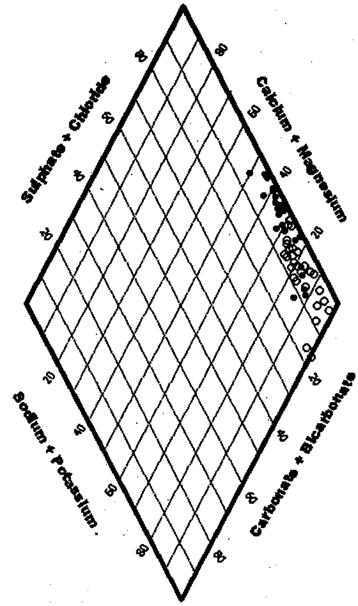

Figure 14B. A trilinear plot of chemical analysis of groundwater samples from the Quaternary Liwa aquifer at liwa (●) and Bu Hasa (O), February 1999.

C

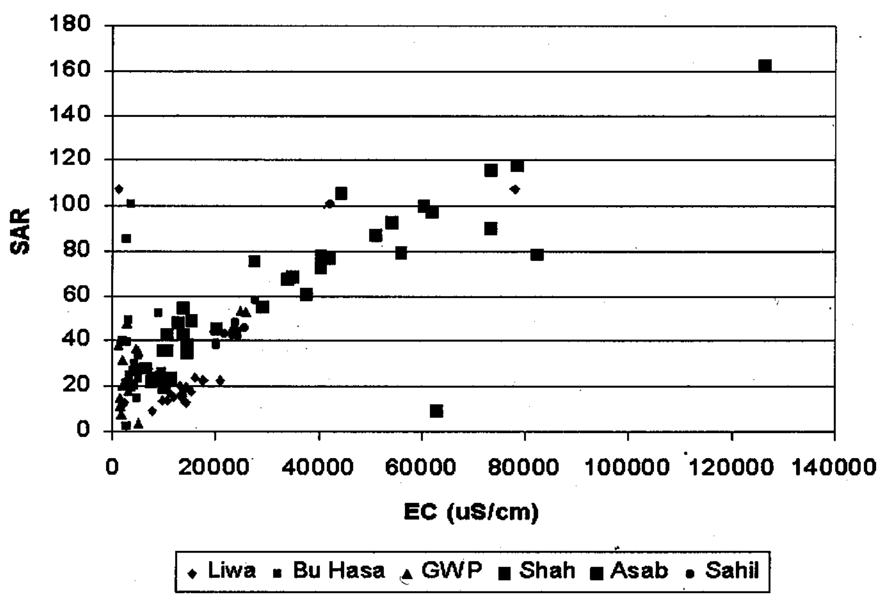

Figure 14C. The EC-SAR relationship of groundwater samples from the Quternary Liwa aquifer at Liwa and Bu Hasa, and Shah, Asab and Sahil oil fields.

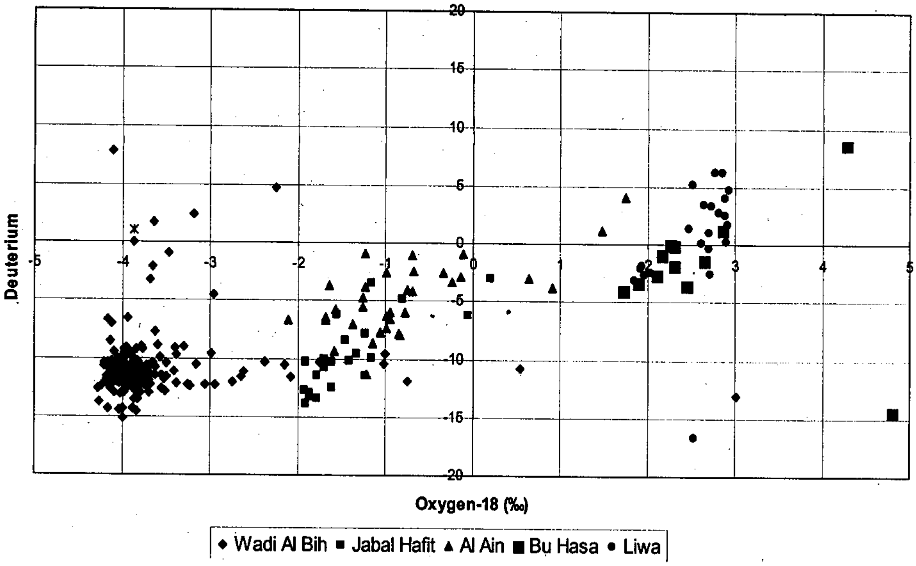

Figure 15. Stable isotopes of the Wadi Al Bih limestone aquifer, Jabal Hafit limestone aquifer, Al Ain gravel aquifer and Quaternary Liwa Aquifer in the Liwa and Bu Hasa areas

Regional Model for the Assessment of Groundwater Flow and Solute Transport in the Irrigated Tadla Plant (Morocco)

Dr. A. Larabi and M. Faouzi (Morocco)

Regional Model for the Assessment of Groundwater Flow and Solute Transport in the Irrigated Tadla Plain (Morocco)

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ABSTRACT

Irrigation of the Tadla plain (central part of Morocco), which started a half century ago, has modified the hydrodynamic equilibrium and the water quality of the phreatic aquifer in the irrigated area. Indeed, this caused rises of the water table, reaching sometimes the soil surface, in addition to nitrate and salt pollution of groundwater due to intensive fertiliser use. The objectives of this study is to assess the water table rise and groundwater pollution by nitrate and salinisation from a mathematical modelling research work by using 1D LEACH code for unsaturated flow and transport simulation in addition to MODFLOW and MT3D codes for saturated flow and transport simulation respectively. A regional model for Beni-Amir aquifer was developed within using MODFLOW and MT3D codes for simulating groundwater flow and solute transport. LEACHC model is used to simulate 1D flow and solute transport in the unsaturated zone to prepare input for MT3D model. The results of simulations show that the irrigation practices within the area is inappropriate due to intensive use of chemical fertilizers which leads to increase the amount of accumulated salts within the soil and the groundwater of Beni-Amir aquifer.

Keywords: Hydrogeology, modelling, groundwater flow, transport, irrigation, salinisation, fertilizers.

1. Introduction and Description of the Study Area

Tadla Plain is an ancient agricultural area and it is part of Beni Mellal Province. It is located 200 km to the south-east of Casablanca city (Fig. 1) with average altitude of 400 m. The area of the plain is about 360 km2 with total population of about 557000 inhabitant in 1994. Today, the water resources in the plain is under great pressure due to the increase of groundwater abstraction in addition to groundwater quality deterioration due to intensive use of fertilizers. Most of the people of Tadla plain are farmers and they are depending on agricultural production as an economic income. Table 1 presents the average amounts of agricultural production types in Tadla plain for the period 1981-1995.

Table 1: Average agricultural production in Tadla plain for 1981-1995 period

Types		**Area (ha)**	**Yield (T/ha)**	**Production *1000T**	**% national Production**
Beet root (irr.)		18.57	44.6	828	30
Cereal	Irrigated Rain fed	42.5 136.82	3.81 0.8	163 109	6 6
Beans		8.52	24.36	208	10
Cotton		9.625	1.74	17	75
Forage	Irrigated Rain fed	17.877 3.034	48.7 11.75	854 36	12 12
Citrus		7.07	17.27	129	11
Olives	Irrigated Rain fed	13.3 1.56	3.9 0.8	52 1.2	10 10

The major part of Tadla plain is agricultural area (more than 3000 km2). About 122403 km2 is irrigated area and 195000 km2 is rain-fed area [1]. The climate in the plain has the Mediterranean semi-arid conditions. The average minimum temperature in winter season ranges between 0-5° and the average maximum temperature in summer season is about 38 C°. The average rainfall rate in the plain is about 350 mm/yr with an average of 55 rainy days/yr. Maximum open pan monthly evaporation is about 302 mm and the minimum is about 52 mm. The average relative humidity is about 63%.

The plain is crossed by two rivers; wadi Oum Er-Rabia from the east to the west with a total length of 160 km and wadi El-Abid from the south to the north with a total length of 20 km. The plain is underlain by two shallow aquifers; Beni-Amir and Beni-Moussa aquifers. The aquifer of Beni-Amir is a shallow aquifer with a surface area about 600 km2. The aquifer is composed of Quaternary deposits that include layers of loess, calcareous, silt, conglomerates and clay. It forms a sloping plain towards wadi Oum Er-Rabia, which ranges in thickness from 40-100 m [2]

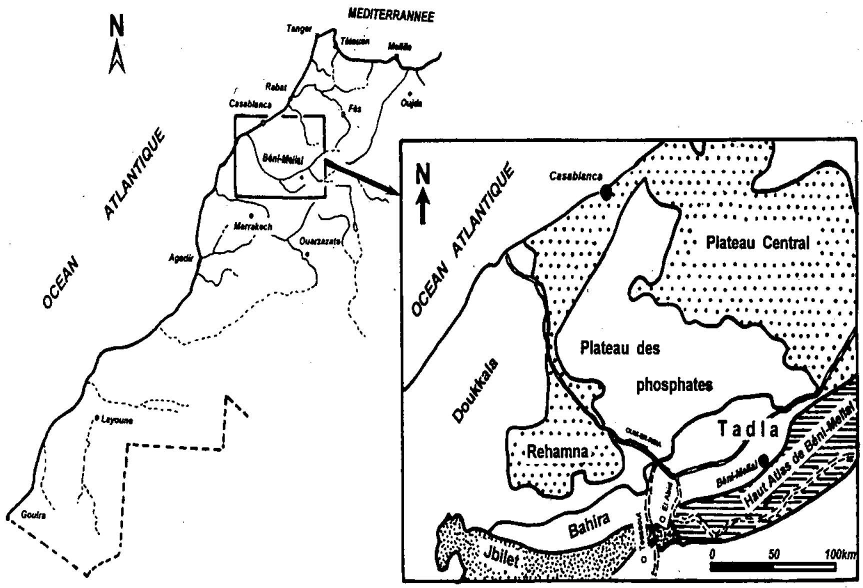


Figure 1: Location map

2. MODEL SET-UP

2.1 *Limits, discretization and aquifer configuration*

According to the geological, hydrogeological, hydrodynamic parameters information, a conceptual model of Beni-Amir aquifer is prepared. This conceptual model is used as the basis for the numerical discretization which will be used in the Modflow [3] and MT3D [4] models. The model domain and finite difference grid was used to simulate groundwater flow in the Beni-Amir aquifer system. The model encompasses an area of about 592 km2 and contains 2368 active cells including 122 boundary cells in XY view (Fig. 2). The model was also discretized vertically into 3 layers. The total number of active cells in 3D view is 7104 finite difference cells.

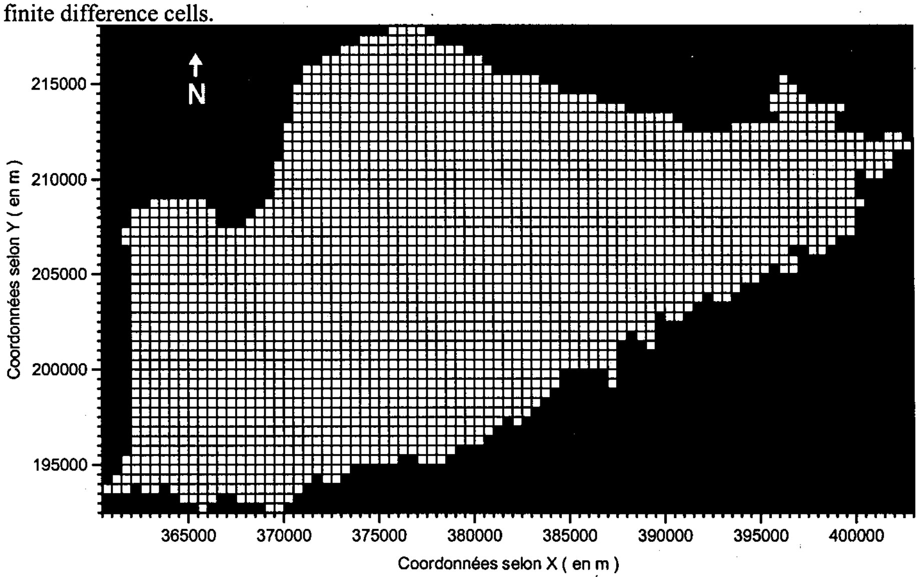
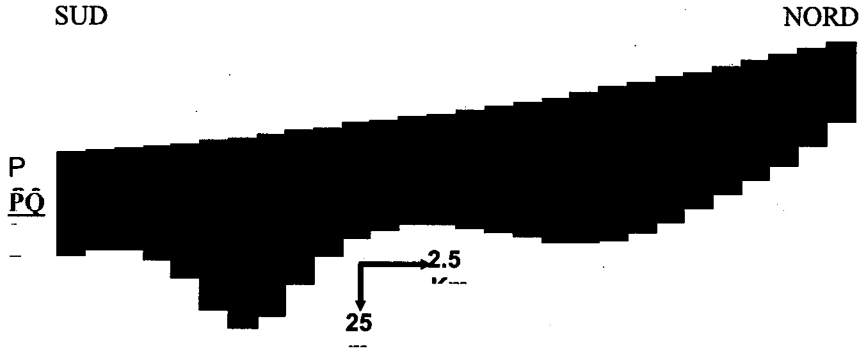


Figure 2: The model domain and finite difference grid in XY view.

The aquifer consists of a complex sequence of Pleistocene age sediments that includes calcareous sandstone, clay, and conglomerates; which are identified in the following three different layers in the aquifer and indicated by PQ1, PQ2 and PQ3 (Fig.3).



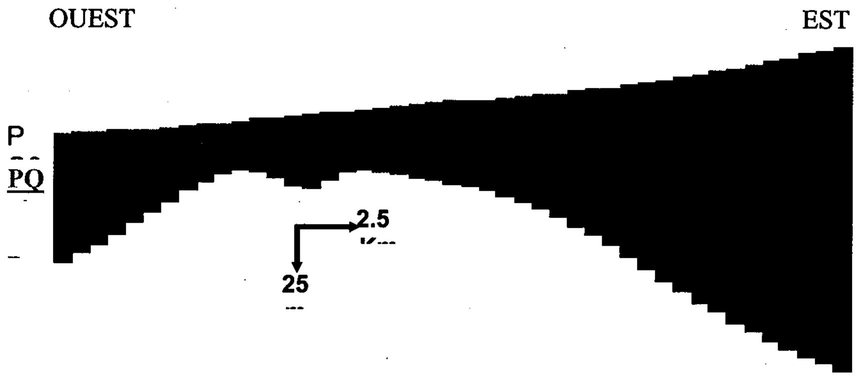


Figure 3: Typical hydrogeological cross sections in Beni-Amir Aquifer.

2.2 Hydrodynamic parameters

Due to the lack of some data and field measurements, average values of the aquifer parameters within the model domain were estimated according to the available data from pumping tests and performance of scientific estimation according to the literature. The estimated values of average horizontal hydraulic conductivity values range between 0.0001-0.00165 m/s and vertical hydraulic conductivity value is estimated to be 0.1 of horizontal hydraulic conductivity. On the other hand average value of storativity (S) is estimated to be in the range of 0.03-0.06 and specific storage in the range of 0.0003- 0.006 /m.

2.3 Boundary conditions and hydrological stresses

No-flow boundary condition is specified along the bottom of the aquifer. A specified constant head boundary condition is affected to wadi Oum-Er-Rabia. The northern and the western boundaries are considered artificially as no-flow boundaries. Two internal conditions are considered in the conceptual model: the groundwater abstraction through pumping wells and the recharge from rainfall and irrigation return flow.

3. STEADY STATE MODEL

3.1 Introduction

According to the available data of groundwater abstraction from Beni-Amir aquifer, the piezometric measurements of the year 1978 [5] can be considered as a steady-state, because there was no significant abstraction amounts registered within that year. Two types of inflows are considered in the model. The natural infiltration from rainfall which is estimated to 28% of the average rainfall (350 mm/yr). The other inflow which comes from the irrigation return flow is estimated by a factor ranging between 20% to 28%. On the other hand, three types of outflows are considered; pumping, direct evapotranspiration and aquifer drainage. Pumping from the aquifer was estimated to be about 15.1 Mm3/yr and the evapotranspiration was estimated according to [6] to be about 660 mm/yr. For the aquifer drainage, there are no available values; and hence values were estimated and tested through the calibration process of the model.

3.2 Calibration Results

Within the model domain 32 monitoring points for groundwater level measurements are basically used in the model calibration [7].The calibration process was performed according to the comparison between calculated and measured water levels in the network of 32 monitoring wells with a permissible difference less than 1 m. The calibration process was done by using trial and error approach depending on assumptions on hydraulic conductivity values. Fig. 4 shows the calibrated results of groundwater levels for the year 1978. The difference between the calculated and measured results was not more than 0.9 m. Table 2 shows the results of the calibrated water balance in 1978 for the Beni-Amir aquifer. Verification of the steady-state model was also conducted using data for the year 1994. The model results agree with the measured water levels. More details on this can be found in the recent work performed by [2].

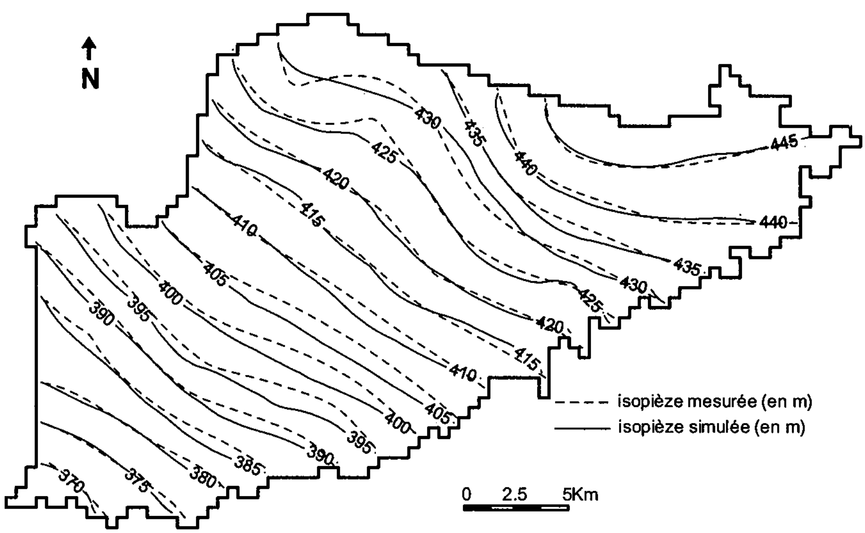


Figure 4a: Calibrated results of piezometric levels in 1978

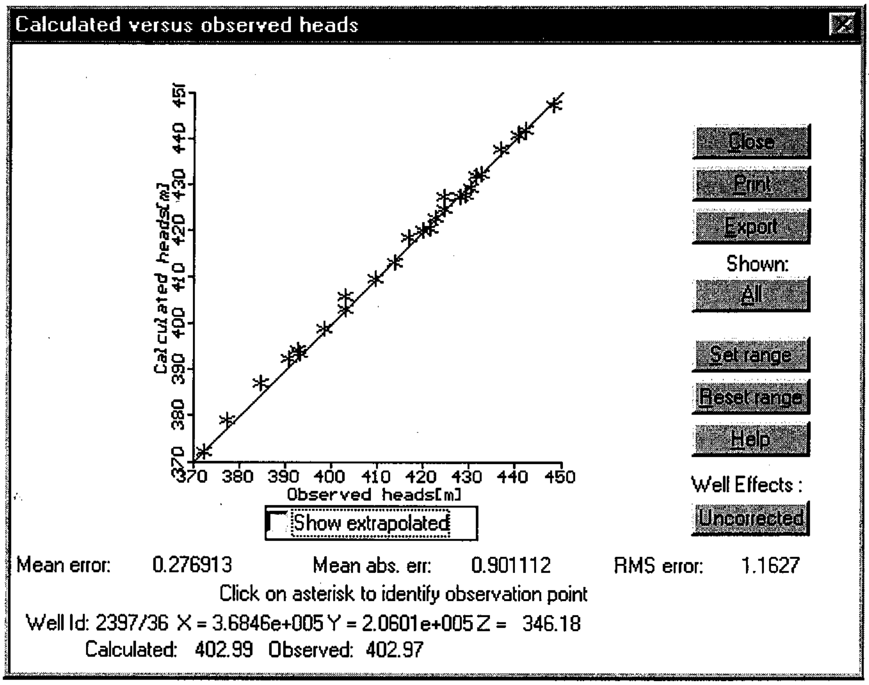


Figure 4b: Calculated versus observed heads in 1978.

Table 2. Calibrated groundwater balance in the year 1978 of Beni-Amir aquifer.

Inflow (Mm3/yr)		Outflow (Mm3/yr)	
Natural recharge	56.4	Natural Drainage Artificial Drainage	65.3 45
Return flow from irrigation	129.5	Agricultural Abstraction Other Abstractions	35.2 15.2
Lateral flow	3.8	Lateral outflow Evaporation	23 5.6
Total	189.7	Total	189.3

4. Set-up of the Transient Model

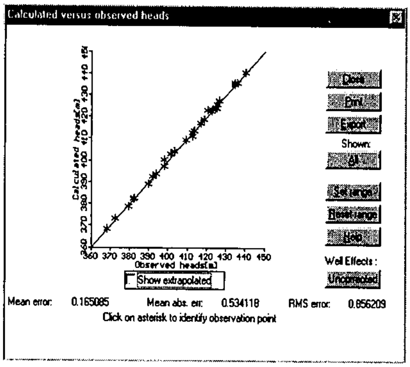
The simulation period was set-up between October 1994 and ending in august 1995, following the irrigation processes. The initial conditions of the transient model for pressure head was taken from the verified output model for year 1994. The calibration of the transient model was done basically by comparison between calculated and measured water levels (Fig. 5). The process was done by estimating the values of storage and specific storage coefficients respectively S and Ss. Table 4 shows the calculated water balance from the model for 94-95, while Table 5 gives the variation of stock through the simulation period (Sept 94–August 95).

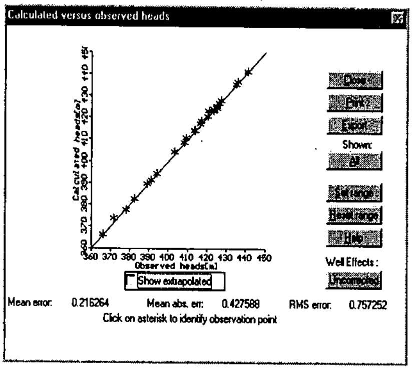
Table 4. Calibrated groundwater balance in 1994-1995

Inflow (Mm3/yr)		**Outflow (Mm3/yr)**	
Storage	76.6	Storage	72.2
Natural recharge	31.3	Natural drainage	45.5
Return flow	120.4	Agricultural Abstraction	91.5
		Other Abstractions	7.9
Lateral inflow	10.1	Lateral Outflow	18.6
		Evaporation	3.5
Total	234	Total	234

Table 5. Variation of stock ($x10^6$ m3) through the transient model simulation period

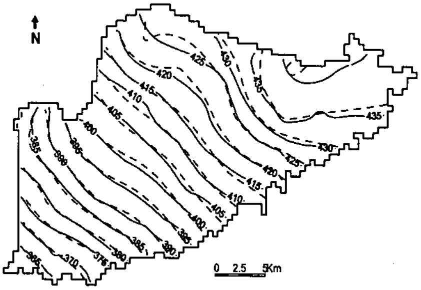
Period	**Variation of stock**	**Period**	**Variation of stock**
9/1994	0.018	3/1995	-0.064
10/1994	0.024	4/1995	0
11/1994	-0.016	5/1995	-0.16
12/1994	-0.032	6/1995	0.08
1/1995	-0.056	7/1995	0.096
2/1995	-0.064	8/1995	0.096

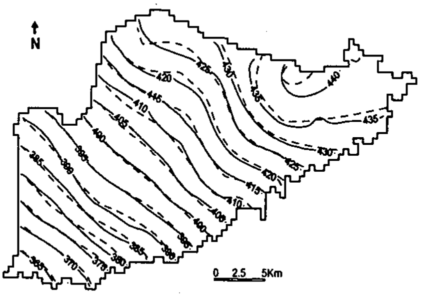




October 1994

August 1995





October 1994

August 1995

Figure 5: Calculated versus observed heads in 1994-1995

5. Transport Model of Beni-Amir Aquifer

5.1 Introduction

The MT3D model is used to simulate impact of irrigation return flow and solute transport within the domain of Beni-Amir Aquifer. In this scenario, the aquifer is considered to have the same configuration of 3D transient flow model. The initial conditions are taken from 1994-1995 transient simulations. The period of the transport model simulation was between 1995 to 2005. We limited the MT3D code simulation to two solute transport chemical elements (Chloride and Sodium), which appear to be responsible for groundwater salinisation in the Beni-Amir aquifer.

In fact, Chloride and sodium are considered in this study, due to the following factors:

- Significant amount of surface water is used in irrigation and comes from outside the domain of the aquifer (wadi Oum-Er-Rabia). The quality of this water has considerable amount of NaCl;
- The top of the aquifer has also considerable accumulated amount of NaCl;
- The correlation ratio between NaCl and the water salinity is found to be high, and ranging between 65% and 90 %t, this gives a general relationship between NaCl and the groundwater quality;
- The solubility ratio of NaCl in water is high, and
- NaCl concentration in groundwater can also help in identifying the sources of solutes (originally from geological formation).

5.2 Model Characterization

Transport of pollutants generally occurs due to convection, diffusion and dispersion processes; but the major process in transport is the dispersion mechanism. The simulation process in the Beni-Amir aquifer was performed with daily transient simulation for the period 1995-2005. There is no available measured values for the transport model parameters, so values were estimated according to literature values taking into consideration the aquifer configuration and characteristics.

The values for molecular coefficient are chosen to be13.3*10^{-2} for sodium and 20.3*10^{-2} m^2/s for chloride based on the works of [8] and [9]. The longitudinal hydraulic dispersivity (D_L) is estimated to be about 0.76 m [10]. Regarding transversal dispersion coefficient and vertical dispersion coefficient; they are estimated to be equal 0.1*D_L and 0.5*D_L respectively.

The LEACHC code [11], one dimensional unsaturated model, was used to simulate the unsaturated transport in order to estimate the amount of salts and the concentration of the aquifer recharge which is coming from irrigation return flow. On the other hand the initial concentrations of salts in groundwater are considered from the measurements in the monitoring network (41 points) for the year 1995 after processing Kriging geostatistical analysis (Fig. 6).

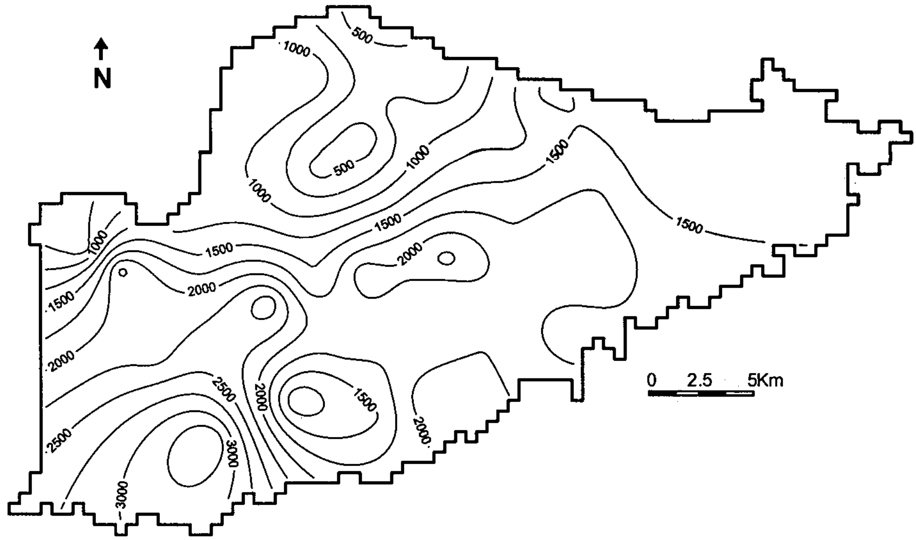


Figure 6: Initial chloride concentrations (mg/l) in Beni-Amir aquifer for November 1995.

5.3 Results and Interpretation

Through the transport simulation using MT3D code, the accumulated amounts of sodium and chloride are calculated for the period 1995-2005. Accordingly, deteriorated areas due to high level of salts accumulated are identified. Figures 7 illustrates the distribution of chloride concentration (1000-5000 mg/l) in the simulated area; for which high values are observed downstream of the area. While Figure 8 shows the temporal variation of chloride concentrations in some selected monitoring wells (upstream, centre and downstream of the study area). It is important to note that cyclic oscillations (on the intra yearly level) are registered in some monitoring wells at the centre of the area. This is due to periods of spreading irrigation in some areas, which correspond generally to two episodes : one between December and May with less irrigation, followed by a second episode for the rest of the year where irrigation is intensively used.

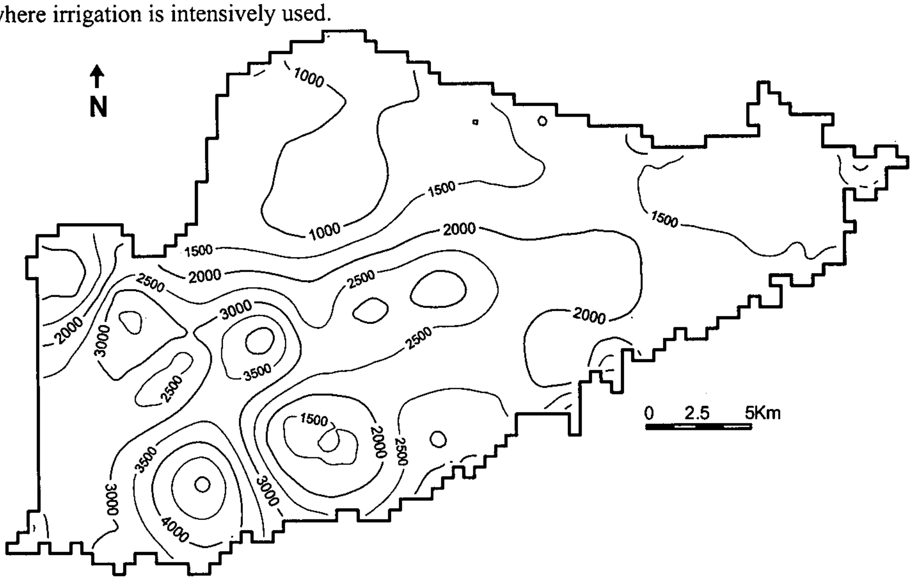


Figure 7: Simulated chloride concentration (mg/l) in Beni-Amir Aquifer in 2005.

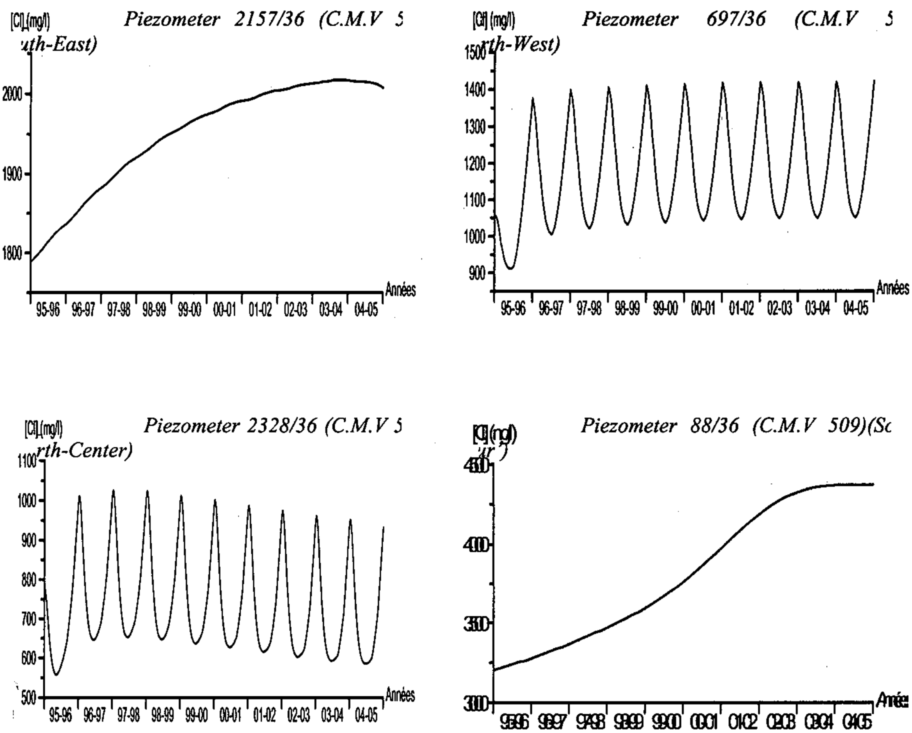


Figure 8: Simulated chloride concentrations in some observation wells (1995-2005)

6. Conclusion and Recommendations

The hydrogeological analysis has led to a good definition of the hydrogelogical behaviour of the aquifer. From this study, two specific areas have been identified, where the water table level is permanently close to the surface (< 2 m) ; they are located at the south-east and south-west of the area. The water table rise in these zones is due to the practical irrigation techniques, associated to a no suitable artificial drainage. Hence, groundwater and soil have became salty. The risk of groundwater salinization is indicated by high concentrations (TDS ≅1500 mg/l); this is due to the irrational and no suitable uses of fertilisers and the classic irrigating technique.

A study by 1D mathematical model of the unsaturated zone (LEACHC) has been performed and has shown the chemical composition of the soil solution and the chemical elements parcelling towards groundwater. The results show also that recycled groundwater increases the sodicity of the soil and the salinization of soil and groundwater.

A 3D mathematical models (MODFLOW and MT3D), based on finite difference method, for groundwater flow and solute transport in the phreatic aquifer has been developed in steady state and transient conditions. The transient groundwater flow model was able to define the intra-yearly evolution and to verify the data coherence. For solute transport in the phreatic aquifer, the MT3D and LEACHC codes have been used. Predictive simulations have been performed for chlorides and sodium transfer in groundwater until the year 2005. The results of these simulations shows that the present irrigation management is inappropriate and is leading to a more quality degradation of groundwater and soil which cannot maintain a sustainable management of the cultivated irrigated area of the Tadla plain. The results show also that a clear rational and sustainable management of water resources is necessary, by minimising salt and nitrate pollution and monitoring the water table rise.

The most important two recommendations coming out from this study are:

- Extension of the model domain is needed in order to include all the Tadla Plain area. This will cover the two aquifers; Beni-amir aquifer and Beni-Mousa aquifer and will increase the accuracy of modelling results.

- The artificial drainage within the model domain shall be considered in future simulation by using MODFLOW.

ACKNOWLEDGEMENTS

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Remediation of Groundwater Contaminated with Phthalates by advanced Oxidation Technology

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REMEDIATION OF GROUNDWATER CONTAMINATED WITH PHTHALATES BY ADVANCED OXIDATION TECHNOLOGY

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Abstract

This study was conducted to assess the removal efficiency of phthalates from contaminated groundwater using a new approach namely: the advanced oxidation technology. This technology is based on the generation of a highly reactive hydroxyl radical (OH^o) that can attack the organic pollutant and degrades it completely to CO_2 and water. In this study, both Fenton's reagent (i.e. H_2O_2/Fe^{2+}) and ultraviolet/hydrogen peroxide (UV/H_2O_2) processes were used to generate the hydroxyl radicals. Dimethyl phthalate (DMP), with an initial concentration of 20 ppm, was used as a model compound. A low-pressure mercury UV lamp of 100 mWatt intensity was used to provide the radiation. The results showed that while both processes were effective in removing phthalates from pure water, only the (UV/H_2O_2) process was effective in removing the contaminant from groundwater. The inefficiency of Fenton process was attributed to the high concentrations of the carbonates, sulfates and chlorides that were detected in the groundwater. These chemicals inhibit the action of the hydroxyl radical on degrading the target compound. However, in the UV/H_2O_2 process, direct photolysis by UV light played a major role in removing the phthalates from groundwater. The UV/H_2O_2 technique can be utilized in the remediation of polluted groundwater with phthalates.

Key Words: Ultraviolet light, hydrogen peroxide, hydroxyl radical, phthalates, UV/H_2O_2 process, Fenton's reagent, advanced oxidation processes, groundwater.

INTRODUCTION

The Kingdom of Saudi Arabia and its neighboring countries are located in an arid region where scarcity of water is a major challenge towards reaching a sustainable development of such countries. Groundwater represents the major source for drinking, industrial and irrigation purposes. Protection of this valuable source from pollution represents an important goal for water authorities, planners and decision makers. The high standard of living in modern societies has resulted in continuous generation of huge amount of wastes, which may contain harmful substances that have adverse effects on human health if they are introduced into the environment. Harmful chemicals such as heavy metals, Benzene, Toluene, Ethyl benzene and Xylenes (BTEX), Methyl Tertiary butyl Ether (MTBE), Poly Aromatic Hydrocarbons (PAHs), phenols, pesticides, and Polychlorinated Biphenyls (PCBs) can leach into groundwater during production or after disposal, and become ubiquitous pollutants.

Phthalates, also called esters of phthalic acids, are formed by linkage of an alkyl group to the carboxylic group. They are environmentally ubiquitous pollutants with a variety of industrial uses including carrier for pesticides and insecticides and insect repellent, and are used in cosmetics fragrances, lubricants, de-foaming agents and as plasticizers added to the polyvinyl chloride (PVC) and plastics to improve their flexibility [Staples et al, 1997]. These chemicals are suspected to cause health problems. In recent years, there has been a growing interest on the safe use of phthalates as additives in many products including PVC pipes, baby feeding bottles, and blood collection bags. In fact, due to their carcinogenic properties, six (6) phthalates have been included in the priority pollutant list set by the U. S. Environmental Protection Agency [Cartwright et al, 2000]. In this study, Dimethyl phthalate (DMP) shown in Figure 1 was used as a target compound.

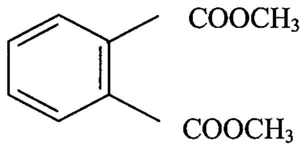

Figure1: Di Methyl Phthalate (DMP)

The interest in developing Advanced Oxidation Processes (AOPs) in chemical water treatment has grown recently [Tedder et al, 1997]. These processes generate highly reactive hydroxyl radicals (OH^o) to oxidize various compounds in the water. The generated radicals are characterized by having a high oxidation potential (2.8 V) that can, in some cases, completely mineralize contaminants by converting them into CO_2 and H_2O [Ruppert et al, 1994]. Several AOPs processes can generate the hydroxyl radicals including: UV/H_2O_2, Fenton's reagent (Fe^{2+}/ H_2O_2), peroxone (ozone / H_2O_2), and titanium dioxide (TiO_2)-assisted photo-catalytic processes [Venkatadari et al, 1993; Rajeshwar, 1995].

In Fenton's reagent, OH^o radicals are formed as a result of the reaction between hydrogen peroxide (H_2O_2) and ferrous ions (Fe^{2+}), while in the case of UV/ H_2O_2 they are formed by a single-step dissociation of H_2O_2. Hydroxyl radicals can oxidize organics (RH) by abstraction of protons producing organic radicals (R^o) and can eventually degrade them into CO_2 and water. In addition, UV light alone can be utilized in the degradation of organic pollutants in a process called photolysis.

In general, little attention has been given to the treatment of phthalates by chemical methods and most research work was directed toward biological treatment [Jianlong et al, 1996].

However, theses methods suffer from several drawbacks such as toxicity of phthalate to microorganisms [Madsen et al, 1999, O'Conner et al, 1989] and the long residence time needed to achieve appreciable removal. Extensive literature search showed that research in the area of degrading phthalate esters by photo-oxidation is lacking. Moreover, the efficiency of these techniques in eliminating pollutants if they exist in groundwater needed to be investigated further. Thus, the main objective of this study was to assess the removal efficiency of phthalates from contaminated groundwater using Fenton's reagent (i.e. H_2O_2/Fe^{2+}) and ultraviolet / hydrogen peroxide (UV/H_2O_2) processes.

MATERIALS & METHODS

The bench-scale photo-reactor consists of a 1.2-L cylindrical vessel made of Pyrex surrounded by an outer Plexiglas cylindrical vessel used for cooling purposes as shown in Figure (2). A low-pressure mercury UV lamp irradiating at a wavelength of an average of 254 nm with an output intensity of about 100 mWatt is used for illumination purpose. The reactor works in a batch mode. The residual DMP concentrations were measured at 0, 15, 30, 45 and 60 minutes.

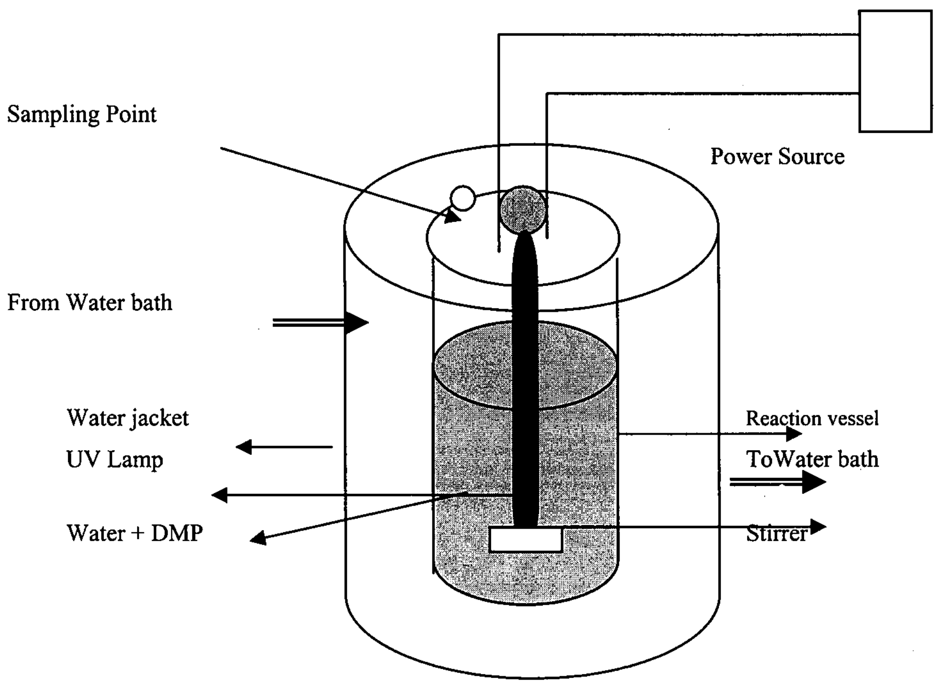

Figure 2: Bench-Scale Photo-Reactor

Neat solution of DMP (99% purity) was used to prepare stock standard dilutions. Aliquots of 20 ppm DMP were spiked in a de-ionized distilled water. Stock hydrogen peroxide (H_2O_2) of 35% purity was used in the experiments [Bassett et al, 1978]. Ferrous sulfate ($FeSO_4.7H_2O$) from Riedel-De Haen AG solution was used to prepare a stock of ferrous ions (Fe^{2+}). The Fe^{2+} stock solution was prepared on daily basis and few drops of 0.01 M sulfuric acid were added to the stock solution in order to prevent oxidation ferrous ions (Fe^{2+}) into ferric ions (Fe^{3+}).

The concentration of DMP in water was determined, after being extracted with a mixture of methylene chloride/hexane (v/v 1:3), by a Gas Chromatograph (GC) equipped with a Photo-Ionization Detector (PID). A30 m long, 0.53 mm i.d. DB-5 fused silica capillary column, was used for the separation purpose. The oven temperature was programmed from 80 °C to 200 °C at a ramp rate of 20 °C. Both detector and injector temperatures were set at 280 °C. Helium gas was used as a carrier at a flow rate of 3 mL and a makeup of 27 mL.

RESULTS AND DISCUSSION

Removal of DMP by Fenton's Reagent

The efficiency of Fenton process in removing DMP from a contaminated groundwater compared to that of pure water was investigated by conducting two experiments. In the first one, a pure water sample was spiked with 20 ppm of DMP and transferred to the photo-reactor. Temperature and pH of the solution was adjusted at 25°C and 3.0 respectively. An amount of 11.2 ppm of Fe^{2+} was then added to the solution followed by a gradual addition of 68 ppm of H_2O_2. Samples were taken at certain reaction times and analyzed for residual DMP. In the second experiment, a groundwater sample was spiked and the rest of the steps were exactly the same as in experiment one. The results of these two experiments are shown in Figure 3.

It can be noticed that Fenton system was completely inefficient in removing DMP from groundwater in contrary to the case of pure water. Basically, there was no removal of DMP from groundwater after a reaction time of 60 minutes. However, under the same conditions, more than 80% of DMP spiked in pure water was removed after 60 minutes of reaction time. It is true that OH^{o} radicals oxidize dissolved target compounds at high reaction rates on the order of 10^9 $M^{-1}S^{-1}$, however, the efficiency of oxidation can be reduced by scavengers of hydroxyl radicals [Ma and Fredrick, 1996]. Scavengers, or inhibitors, of hydroxyl radicals are these compounds (other than the target compound) that have a reasonably high rate of reaction with OH^{o} radicals. These compounds will be involved in reactions with the OH^{o} radicals and deplete a certain amount of it. This will negatively affect the reactivity of OH^{o} radicals with the target compounds. For example, carbonate and bicarbonate ions have reaction rates of 1.5×10^7 $M^{-1}S^{-1}$ and 4.2×10^8 $M^{-1}S^{-1}$, respectively, with OH^{o} radicals [Staehelin and Hoigne, 1985]. This is probably the main reason for the low efficiency of Fenton's process when the pollutant is spiked into the groundwater sample which has chemical characteristics listed in Table 1. It seems that the high concentrations of chlorides (1498 ppm), sulfates (752 ppm), bicarbonates (145 ppm) and phosphates (126 ppm) inhibited the OH^{o} radical from attacking the target compound (DMP), which has a concentration of only 20 ppm.

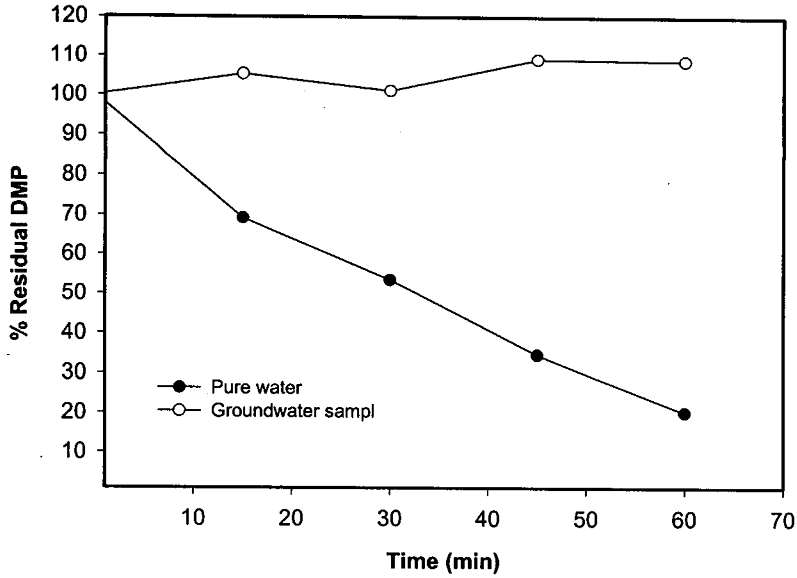

Figure 3: Removal of DMP from Pure and Groundwater by Fenton Process

Table 1: Characteristics of Local Groundwater Sample

Analyte	**Concentration (ppm)**	**Analyte**	**Concentration (ppm)**
Sodium (Na^{+})	1347.8	Bicarbonate (HCO_3^{-})	145
Magnesium (Mg^{+2})	96.196	Chloride (Cl^{-})	1498
Calcium (Ca^{+2})	293.7	Sulfate (SO_4^{-2})	752
Total dissolved solids (TDS)	3640	Phosphate (PO_4^{--})	126

Removal of DMP by UV/H_2O_2

In this part of the study, the efficiency of UV/H_2O_2 process in removing the target compound was investigated. To systematically study the efficiency of this process, it was decided to first examine the effect of UV direct photolysis (i.e. UV only). To accomplish this, an experiment was conducted in which water sample spiked with 20 ppm of DMP was irradiated by UV light for 60 minutes. The results depicted in Figure 4 shows that an appreciable amount of DMP was removed due to UV photolysis mechanism only. In fact approximately 60% of DMP was removed due to photoloysis only. This means that DMP can be decomposed to a certain extent by direct photolysis action only. The DMP compound was found to absorb UV light fairly well in the range of 240 to 260 nm, which made it a good candidate for photodegradation.

In order to evaluate the efficiency of UV/H_2O_2 process in removing DMP if it exists in either a groundwater or pure water samples, two experiments were conducted. In both experiments, the spiked pure and groundwater samples were first dosed with an initial concentration of 68 ppm of H_2O_2 before exposure to irradiation by UV light, while keeping other parameters constant. The results are plotted in Figure 5.

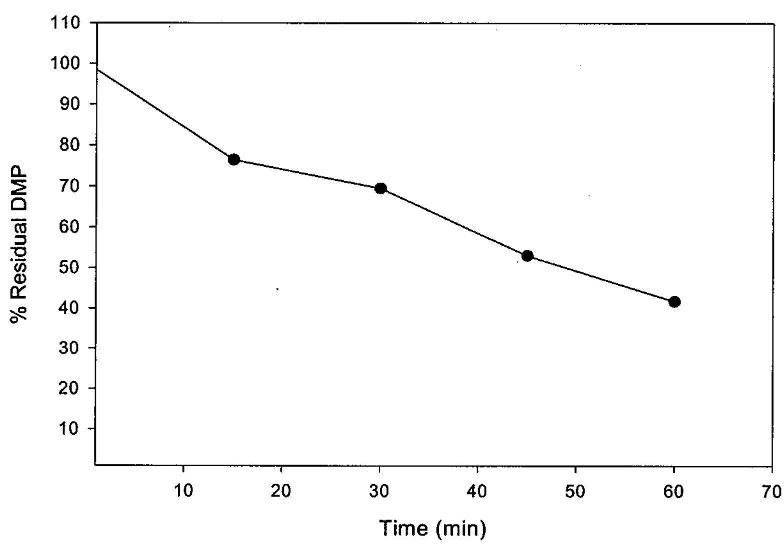

Figure 4: Removal of DMP by Direct Photolysis

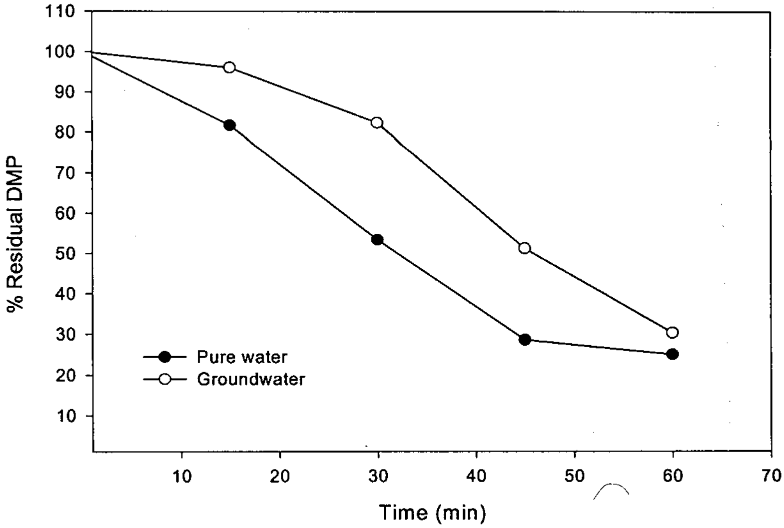

Figure 5: Removal of DMP by UV/H_2O_2 Process from Pure and Groundwater

The data depicted in Figure 5 shows that the efficiency of UV/H_2O_2 process in removing DMP from pure water is slightly better than that from groundwater sample. For example, after 60 minutes, more than 65% of DMP was removed from the ground water sample and more than 70% of DMP was removed from pure water sample.

The minor drop in efficiency of UV/H_2O_2 process in removing DMP from groundwater can be attributed to the presence of some inorganic chemical compounds, such as carbonates and sulfates that are known to react with OH^o radicals and tend to deplete some of the radicals formed by UV/H_2O_2 process. According to the conclusion reached above, the removal of DMP by UV/H_2O_2 process seems to be not solely due to the reaction with OH^o radicals and that other removal mechanisms such as direct photolysis by UV plays a significant role in the degradation of DMP. From here comes the efficiency of UV/H_2O_2 in degrading DMP in pure as well as groundwater samples.

By comparing Figures 4 and 5, it can be noticed that the removal pattern of DMP by UV alone is different than the removal pattern by UV/H_2O_2 system. Figure 4 shows that UV alone removed DMP in fairly constant rate. However, the removal rate in the case of UV/H_2O_2 system was higher initially then it continued at a slower rate as shown in Figure 5. This can be explained by the fact that the decomposition of DMP by UV alone may have occurred via photo-dissociation caused mainly by the intense energy of the UV light. However, in the UV/H_2O_2 system, additional factors such as oxidation by H_2O_2 and OH^o radicals was introduced which enhance the removal of DMP even further. Ultraviolet light in the UV/H_2O_2 system can also facilitate the reaction between DMP and OH^o radicals formed from the dissociation of H_2O_2 molecules by initiating a series of reactions that involve various organic radicals (R^o) as well as OH^o radicals. The intermediates formed due to the decomposition of DMP can also affect the extent and removal pattern of DMP since these intermediates may have different reaction rates with OH^o radicals. The overall conclusion is that the removal of DMP by UV/H_2O_2 system has been enhanced by the collective actions of UV light and OH^o radicals.

CONCLUSION

This study investigated the removal efficiency of dimethyl phthalates (DMP) from groundwater using advanced oxidation process. The results showed that up to 60% of the 20 ppm of DMP was removed by direct photolysis. However, the removal efficiency was enhanced when hydrogen peroxide (H_2O_2) was utilized along with the UV irradiation. More than 75% of DMP was removed after 60 minutes of reaction time when 68 ppm of H_2O_2 was applied. On the other hand, Fenton's process failed to remove the target compound from groundwater due to the presence of inorganic salts that inhibited the action of the hydroxyl radical.

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Use of Multivariate Statistical Methods in Assessing Groundwater Quality: Examples from Saudi Arabia

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Use of Multivariate Statistical Methods in Assessing Groundwater Quality: an example from Saudi Arabia

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ABSTRACT

The quality of groundwater is controlled by many factors among which the most important are aquifer geology, interaction between groundwater and the aquifer material, influence of land use activities on the area. A commonly used approach in assessing groundwater quality is the use of scatters diagrams (i.e. X-Y plots) of different ionic species. The next step is classification of groundwater into facies based on the major dissolved constituents. These techniques give an idea on the geochemical evolution of groundwater. Since many variables affect the chemistry of groundwater, the relationships between these variables and their effects on each other can be handled by using multivariate statistical techniques. This paper deals with the application of cluster analysis, principal components and factors analysis, to groundwater chemistry of Al-Ulla area in Saudi Arabia. Two main clusters were figured out, the first is related to chloride, sodium, sulphate, magnesium, calcium, potassium, silica and bicarbonate ions. The second cluster is due to pH and nitrates in the groundwater samples. Three factors were found responsible for the overall mineralization of groundwater. The is due to sodium, chloride, sulphate and boron ions. The second factor indicated recharge from rainfall. The third factor is due to effects of irrigation and waste water.

Key words: Multivariate analysis; cluster; factor analysis; groundwater

Introduction

Groundwater chemical composition is usually affected by a number of factors. The most important of which are: 1) aquifer geology, rock types in the area: 2) degree of chemical weathering of rock types. 3) interaction between groundwater and aquifer material; 4) inputs from sources other than water rock interactions; 5) influence of land use activities on the area. Several conventional methods of data analysis exist for groundwater quality assessment; they include pictorial diagrams, multivariate diagrams and diagrams combined with maps or cross-sections. The pictorial diagrams are suitable for the simple representation of physical or chemical properties of a particular aquifer. They represent single variable analysis. Pictorial diagrams include bar graphs, circular and radial diagrams. Multivariate diagrams bring together the results of analyses of major ions for different water samples and permit direct comparison of various groundwater types, facies, genetic and classification statements. They include trilinear, square, rectangular and parallel scale diagrams (Matthess, 1982). Diagrams combined with maps or cross-sections show representation of individual values or analyses by lines of equal concentrations or equal ionic ratios; distribution of groundwater types, facies and so on. All these techniques are generally restricted to the major ions composition of the groundwater. These conventional techniques ignore minor ions and trace elements, which may be important for hydrochemical evaluation. In view of this limitation and increasing number of physical and chemical variables in groundwater, multivariate statistical methods are looked for as powerful techniques for groundwater quality assessment and evaluation. These techniques were successfully applied to different hydrochemical data for solving different problems, such as characterization of hydrochemical systems and groundwater contamination (Subbarao et al., 1996; Suk and Lee, 1999; Voudouris et al., 2000). The multivariate techniques do not provide information on the origin and chemical evolution of groundwater statistical groups (Güler et al., 2002). The most widely used and helpful techniques are clustering, principal component and factor analyses.

Clustering deals with the classification of objects into more or less homogenous groups in a manner so that a relation between groups is revealed. For each object a series of measurements constitute data set; n objects and m measure characteristics form an n x m matrix. Some measures of similarity can be computed between every pairs of objects. Several coefficients of similarities are used. These include correlation coefficient, and Euclidian distance. Correlation is the ratio of covariance of two variables to the product of their standard deviation. Thus the correlation coefficient:

$$r_{jk} = \frac{COV_{jk}}{S_j S_k} \qquad [1]$$

where COV_{jk} is the covariance for variable j and variable k to the and S_j and S_k is their respective standard deviations.

The Euclidean distance:

$$d_{ij} = \left(\frac{\sum_{k=1}^{m} (X_{ik} - X_{jk})^2}{m} \right)^{1/2} \qquad [2]$$

where X_{ik} denotes the K^{th} variable measured on object i, X_{jk} is the K^{th} variable measured on object j.

A low Euclidian distance indicates that the two objects are similar where large distance indicated dissimilarity. Commonly the $n \times m$ data matrix is standardized prior to computing similarity so that each variable is weighted equally. Standardization avoids influence of variables with grater magnitudes. Similarity measurements between all possible pairs of objects results in an n x n symmetrical matrix. Coefficient , C_{ij} in the matrix gives the resemblance between objects i and j. The objects are then arranged hierarchically so that those with the high mutual similarity are placed together. Then groups or clusters of objects are associated with other clusters and so on until all objects have been placed into a complete classification scheme. The similarity results are usually displayed by construction of a tree-like diagram or dendogram. Dendograms constructed from standardized data both for the correlation coefficient and the distances are generally similar. The correlation coefficient indicates greatest similarity at high positive values; Euclidian distance indicates greatest similarity by the smallest distance. Generally weighted pair group methods tend to be superior to either linkage or unweighted methods.

The main objective of factor analysis is to interpret the structure within the variance-covariance matrix of a multivariate data collection. There are two procedures in factor analysis: R-mode and Q-mode analysis. R-mode analysis investigates inter-relationships in a correlation matrix between variables. Q-mode analysis investigates the inter-relationships between samples (Davis, 1986, Suk and Lee, 1999, Swanson, 2001 and Wang et al, 2001). In factor analysis both R-mode and Q-mode analyses eigenvalues and eigenvectors are extracted from the matrix of correlations or variances. Data are then converted to standardize, or unit less form by subtracting from each observation the mean of the data set and dividing by the standard deviation. The new transformed variables will have a mean of zero and a variance of one. The variance-covariance matrix of the standardized variables is the correlation matrix. The principal components are the eigenvectors of the variance-covariance matrix. They provide inside into the structure of matrix. Factor analyses use principal components as start for factor analysis. The principal components analysis is concerned with finding the principal axes of the ellipsoid (eigenvectors) and measuring their magnitudes (eigenvalues). Because the variance-covariance matrix is always symmetrical, eigenvectors are orthogonal, or oriented at right angles to each other (Fig. 1). The principal axes of the ellipsoid reflect the total variance of the data set. Each of these axes account for an amount of the total variance equal to the eigenvalue divided by the trace. At least one of the axes will be more efficient than any of the original variables; and one of the axes must be less efficient. When the original observation is projected onto the principal axes it is converted to a score. The elements of eigenvectors used to compute the scores are called loadings. i.e. loadings are coefficients of the linear equation defined by the eigenvectors.

In factor analysis the factor model is expressed as:

$$X_j = \sum_{r=1}^{p} l_{jr} f_r + \varepsilon_j \qquad [3]$$

Where f_r is the rth common factors,

p is the specified number of factors,

ε_j is the random variation unique to the original variable X_j,

m is the original variable X_j ; there are m random variables ε_j ; taken together, these constitute the unique factor. The coefficient l_{jr} is the loading of the j^{th} variate on the r^{th} factor. This corresponds to the loadings or weights on principal component analysis.

When factor loadings are arranged in a matrix form they make a factor matrix. The amount of variance of each variable retained in the factor or commonalities is obtained by squaring the elements in the factor matrix and summing the total within each variable. The magnitude of commonalties is dependent upon the number of factors retained. Next step in factor analysis is rotation of the factor axis. Rotation is a technique to rotate factor axis to positions either near extremities or near the origin. Factor loadings are adjusted so that either near + or –1 or near zero (Kaiser, 1958; Davis, 1986). Rotation thus involves maximization of the loading on the factors. This implies maximizing the range of loadings. Rotation of factor axis is performed iteratively. It preserves essentially the orthogonality of the factor axis.

In Q-mode analysis a suit of samples is arranged into a meaningful order, so that the relationship between sample and another can be worked out (Cattell, 1965). An n x n matrix of similarities between samples is created. In Q-mode analysis a common measure is the cosine theta coefficient, $\cos\theta_{ij}$.

$$Cos\theta_{ij} = \frac{\sum_{k=1}^{m} X_{ik} X_{jk}}{\left(\sum_{k=1}^{m} X_{ik}^2 \sum_{k=1}^{m} X_{jk}^2\right)^{-2}} \quad [4]$$

Where:

X_{jk} is the k^{th} variable of the i^{th} observation,
m is the number of variables,
i and j are samples,
$Cos\ \theta_{ij}$ is the cosine of angle between vectors of these two points.

Principal axes are extracted as explained earlier. After factors being extracted they are then rotated.

The main purpose of this paper is to illustrate the application of multivariate statistical methods in assessing groundwater quality. Cluster analysis, principal components and factor analysis were applied to groundwater samples collected from the Al-Ulla area in northern Saudi Arabia.

Methods of Data Analysis

The multivariate statistical methods used in this study were performed, using the standard statistical software Minitab (1996), SPSS (1999), and STATISTICA (1995).

Cluster Analysis

Cluster analysis of the data was performed in Q-mode in order that the similarity between specimens can be discovered. The similarity coefficient used was the Euclidean distance function. To reduce the number of variables used in calculating the distance function, the calculation was performed on the scores of varimax rotation. The results were presented in the form of dendogram showing the degree of similarity between specimens and groups of specimens. Hierarchal clustering was performed using all variables, using anions concentrations only, and finally using cations concentrations only.

Factor Analysis

The data was analyzed in R-mode and the results were output as:
a) Loadings on all the variables (ionic concentrations) of the varimax factors obtained from a principal components analysis of the raw data. The principal components with roots greater than 1 were selected, as below this value the data provide nothing recognizable as worthwhile.

b) The percentage of the total data variance accounted for each varimax factor.

c) The scores or values of each varimax factor on each specimen.

The values of each of the varimax factor scores could be treated as if the were measures of some hypothetical hydrochemical property of each specimen. The factor analysis was performed three times. The first time was done using all variables. The second time was done using anion concentrations only; and the third one using cations concentrations only. Each time the factor scores of the varimax factors were plotted as distribution map, starting with the factors, which accounts for the highest percentage of the total data variance and therefore might be expected to reveal the most significant hydrochemical variation.

Application

The above mentioned statistical methods were applied to Wadi Al-Ulla which is located in the southwestern most end of the great Nafuad Basin in Saudi Arabia (Fig. 2). Wadi Al-Ulla area is built up of three stratigraphic units (Parson-Basil, 1968 and BRGM, 1985). From the oldest to the youngest, these units are the Precambrian-Cambrian basement complex, the Cambrian-Ordovician Saq Sandstone and the Tertiary volcanic rocks. The Wadi Al-Ulla itself is filled with a thick cover of alluvial deposits of variable thickness. The thickness of these deposits increases from north to south, where it reaches a maximum thickness of 90 meters (Al-Bassam and Al-Alawi, 1994). The water bearing units in the Ulla area is the Saq Sandstone and the alluvial deposits. In the Wadi area they form one hydraulic unit. Figure (3) summarizes the water level configuration in the area. The groundwater moves under an average hydraulic gradient of .006 from some 1000 meters to about 600 meters above the mean sea level. In general it follows the surface drainage pattern. Twenty-five groundwater samples were collected from Wadi Al-Ulla. The samples were obtained from production wells tapping the water bearing units in the area. The collected samples were analyzed for pH and electric conductivity (EC). Laboratorial analyses included determination of major and some minor ion concentrations and total dissolved solids (TDS). The measured ions were calcium, magnesium, sodium, potassium, bicarbonate, chloride, sulphate, nitrate, boron, and silica. Table (1) summarizes the results of the laboratorial analyses.

The total dissolved solids in Al-Ulla groundwater varies from 400 mg/l to more than 1800 mg/l. Salinity increases from the north-northwest towards the south-southeast along the flow direction (Fig. 4). The groundwater is characterized by relatively high concentrations of sodium and chloride. This can be attributed to the concentration of sodium chloride salts in the soil due the high evaporation rate under the hyper-arid climate in the area.

Discussion

Cluster Analysis

The results of cluster analyses of the data from Al-Ulla area are summarized on Table (2) and figures (5-8). Figure (5) shows a dendogram using linkage of Euclidean distance. Figure (6) elaborate on clusters using Ward's Method (Wards, 1963). The two dendograms confirm each other, though Ward's method seems more powerful in identifying the clusters. Two main clusters were figured out. Eighteen samples belonged to the first cluster and seven samples belonged to the second cluster. Table (2) summarizes the final cluster centers for each group. The first cluster is characterized by a relatively low salinity and lower major ions concentrations, when compared with the second cluster. Due to the aridity conditions prevailing in the Al-Ulla area the second cluster seems to include the samples belonging to the shallow wadi alluvial deposits and those samples in the first cluster seem to belong to the Saq Sandstone. The Saq groundwater is known for its better and rather good quality.
Figures 7 and 8 show clustering based on variables. Grouping of variables indicates strong dependence of total dissolved solids (TDS) on Cl, Na, SO_4, EC, Mg, Ca, K, SiO_2, and HCO_3 in their order of linkage. The pH and NO_3 appear as a separate cluster. This separate cluster based on variables seems to be linked with the third factors discussed hereafter.

Factor analysis

Factor analyses of groundwater chemistry of the Al-Ulla area are summarized on Table (3) and figures 9 and 10. The first factor accounts for about 62% of the total variance in the varimax rotation. It reflects high landings for TDS, Na, Cl, SO_4, and B. Relatively lower loadings are attributed to other ionic constituents. Figure (11) shows the spatial distribution of the first factor score. It coincides with the distribution of total dissolved solids shown in figure (4). The ionic constituents related to this factor are likely to be responsible for the highly mineralized water in the Al-Ulla area. Sodium and Chloride ions indicate evaporation and concentration of sodium in the soil. Dissolution is another process that can be linked to this first factor.

The second factor extracted from the variables accounts to about 14% of the total variance. It does not reveal much additional details of the groundwater flow other an indication of limited recharge to the alluvial from rainfall.

The third factor does not represents more than 8.4% of the total variance. It indicates the effects of irrigation and wastes due to increase of nitrates that appear in this factor.

The factor scores coefficients for the three factors regarding boron are very interesting. Boron seems to be an important minor element in the Al-Ulla groundwater.

Conclusions

Cluster analysis applied to the data of the Al-Ulla area has been found to be strong method to group groundwater samples into clusters that have common chemical characteristics and thus helped in relating samples to their aquifers.
The factor analysis process in the Al-Ulla area has clearly correlated the first factor with the salinity distribution. It has also highlighted the significance of boron which has provided some added information hitherto unrecognized about the flow distribution and style within the aquifer. Thus factor analysis is of special interest regarding the minor constituents of the groundwater.

In conclusion it can be said that the application of multivariate techniques is very useful and informative in the groundwater quality studies.

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Tables and figures captions

Table

1	Groundwater chemistry of the Al-Ulla area.
2	Final cluster center for the Al-Ulla data.
3	Results of factor analysis of the Al-Ulla data.

Figure

1	Ellipse showing vectors and variables.
2	Geological map of the Al-Ulla area.
3	Water level contour map of the of the Saq Sandstone and the alluvial aquifer system in meters above sea level (coordinates are in decimal degrees).
4	Total dissolved solids distribution map (in mg/l).
5	Dendogram using single linkage for samples.
6	Dendogram using Ward's method for samples.
7	Dendogram using single linkage for variables.
8	Dendogram using Ward's method for variables.
9	Scree plot of eigenvalue and factor number.
10	Loading plot of first factor against second factor.
11	Spatial distribution map for score of the first factor.

Table 1 Groundwater chemistry of the Al-Ulla area.

Well No.	pH	EC	TDS	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NO_3	SiO_2	B
1	8.7	500	329	28.00	10.40	70.20	3.90	63.40	90.20	106.00	21.10	24.00	0.4
2	7.9	600	357	40.00	16.40	59.30	5.50	73.20	114.00	106.00	16.10	16.50	0.4
3	8	680	475	64.00	11.30	80.00	4.30	57.30	153.00	144.00	18.60	15.00	0.3
4	7.5	1400	985	100.00	37.20	184.00	8.20	110.00	330.00	307.00	18.00	25.00	0.5
5	7.4	1400	872	60.00	37.20	185.00	12.50	120.00	266.00	283.00	27.90	17.50	0.5
6	7.4	1500	832	68.00	39.60	196.00	8.60	112.00	309.00	288.00	22.90	16.60	0.5
7	7.6	930	622	96.20	24.90	70.80	7.40	65.00	227.00	173.00	22.30	20.60	0.4
8	7.5	1350	1091	123.00	35.70	177.00	15.20	100.00	288.00	384.00	57.70	28.50	0.6
9	7.5	1800	1362	86.40	71.20	312.00	14.80	134.00	508.00	336.00	34.10	41.60	0.6
10	7.2	3400	2963	272.00	94.40	607.00	17.80	89.10	1164.00	787.00	19.20	44.00	0.9
11	7.7	1200	770	130.00	35.50	104.00	3.50	65.90	291.00	197.00	9.90	33.30	0.4
12	8.1	100	596	68.20	27.50	112.00	5.50	105.00	217.00	154.00	13.00	20.90	0.4
13	7.4	2900	1639	101.00	61.70	370.00	18.30	203.00	643.00	432.00	13.60	31.80	0.6
14	7.2	3000	1862	122.00	74.00	434.00	15.20	179.00	643.00	557.00	17.40	29.40	0.7
15	7.2	2700	1682	162.00	56.30	322.00	11.70	143.00	589.00	528.00	13.00	21.60	0.6
16	7.4	3000	2045	127.00	62.20	421.00	24.60	176.00	799.00	595.00	16.10	38.80	0.8
17	7.4	1800	1045	89.80	54.10	177.00	10.50	121.00	401.00	298.00	14.90	25.60	0.6
18	7.7	1300	688	73.80	28.60	116.00	5.10	101.00	195.00	206.00	63.20	19.30	0.5
19	7.6	1400	687	43.00	25.00	162.00	8.60	89.10	217.00	211.00	21.10	19.40	0.4
20	7.3	2900	1841	226.00	95.40	284.00	0.00	106.00	767.00	451.00	18.00	25.70	0.7
21	7.9	1150	762	134.00	20.20	92.90	3.90	117.00	229.00	194.00	35.30	24.40	0.3

22	7.7	660	366	57.00	8.90	71.50	2.00	132.00	110.00	71.50	19.80	29.20	0.2
23	7.7	640	472	66.00	10.70	64.40	3.10	112.00	105.00	106.00	25.40	22.80	0.2
24	7.4	2500	1711	167.00	78.00	311.00	12.10	254.00	685.00	300.00	14.30	31.20	0.4
25	7.6	1050	715	71.20	26.70	110.00	5.90	234.00	179.00	92.20	32.20	24.10	0.3

(raw data were collected from Al-Bassam and Al-Alawi, 1994)

Table 2 Final cluster centers of the Al-Ulla data.

Variable	Cluster 1	Cluster 2
pH	7.72	7.30
EC	1081.11	2914.29
TDS	723.67	1936.29
Ca	77.70	168.14
Mg	28.95	74.57
Na	130.23	392.71
K	7.14	14.24
HCO_3	106.22	164.30
Cl	234.96	755.71
SO_4	203.15	521.43
NO_3	26.31	15.94
SiO_2	23.57	31.79
B	.42	.67

Table 3 Results of factor analysis for the Al-Ulla data.

i) Rotated factor loadings and communalities (Varimax rotation).

Variable	Factor1	Factor2	Factor3	Communality
pH	-0.654	0.437	-0.022	0.62
EC	0.885	-0.362	-0.107	0.926
TDS	0.952	-0.261	-0.1	0.985
Ca	0.852	0.049	-0.172	0.758
Mg	0.888	-0.265	-0.157	0.884
Na	0.913	-0.329	-0.08	0.948
K	0.63	-0.511	0.211	0.703
HCO_3	0.124	-0.947	-0.1	0.921
Cl	0.945	-0.226	-0.19	0.981
SO_4	0.963	-0.153	0.013	0.952
NO_3	-0.105	0.048	0.951	0.917
SiO_2	0.661	-0.262	-0.03	0.506
B	0.928	-0.045	0.123	0.879
Variance	8.0112	1.8754	1.0934	10.98
% Variance	0.616	0.144	0.084	0.845

ii) Factor score coefficients.

Variable	Factor1	Factor2	Factor3
PH	-0.025	0.209	-0.07
EC	0.083	-0.085	-0.039
TDS	0.122	0.018	-0.029
Ca	0.175	0.258	-0.109
Mg	0.104	-0.001	-0.088
Na	0.098	-0.05	-0.012
K	0.014	-0.28	0.249
HCO_3	-0.219	-0.773	-0.074
Cl	0.123	0.047	-0.116
SO_4	0.159	0.112	0.077
NO_3	0.053	0.002	0.898
SiO_2	0.067	-0.057	0.019
B	0.186	0.193	0.179

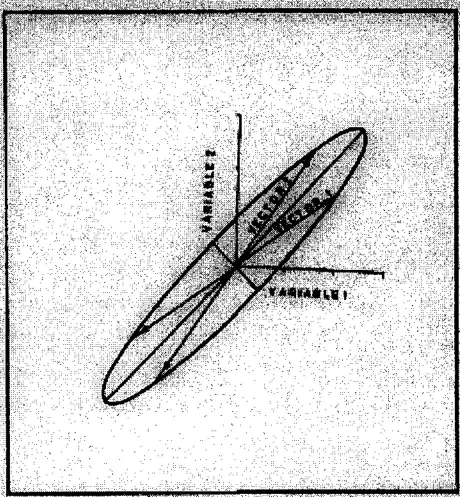

Fig. 1 Ellipse showing vectors and variables.

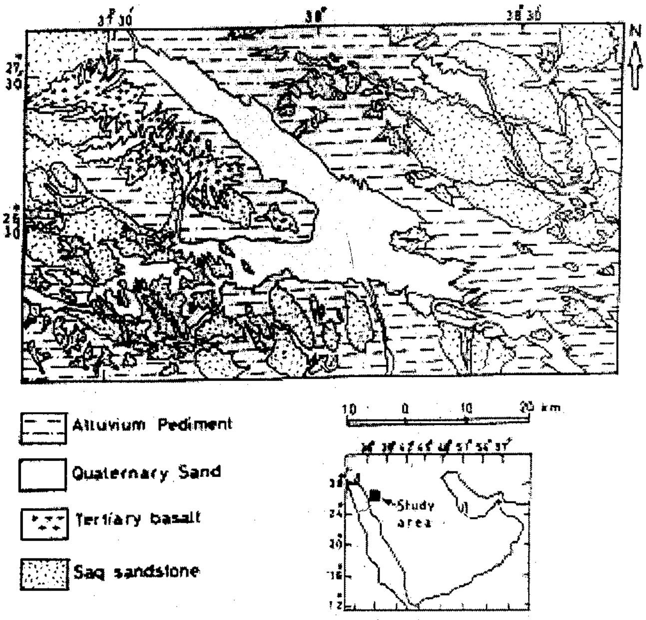

Fig. 2 Geological map of the Al-Ulla area.
(modefied after Al-Bassam & Al-Alawi, 1994)

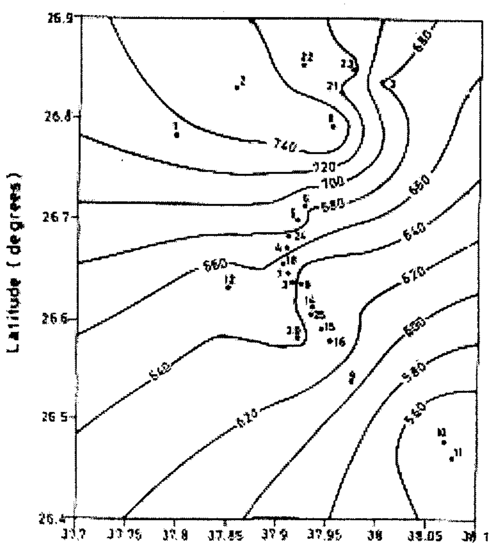

Fig. 3 Water level contour map of the Saq sandstone and the alluvial aquifer system in meters above sea level.
(Coordinates in decimal degrees)

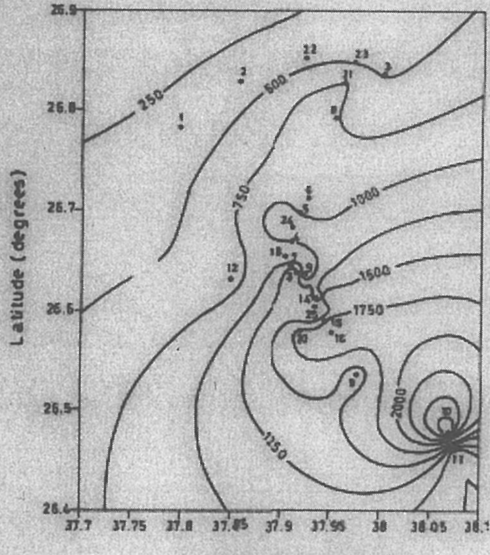

Fig. 4 Total dissolved solids distribution map (in mg/l).

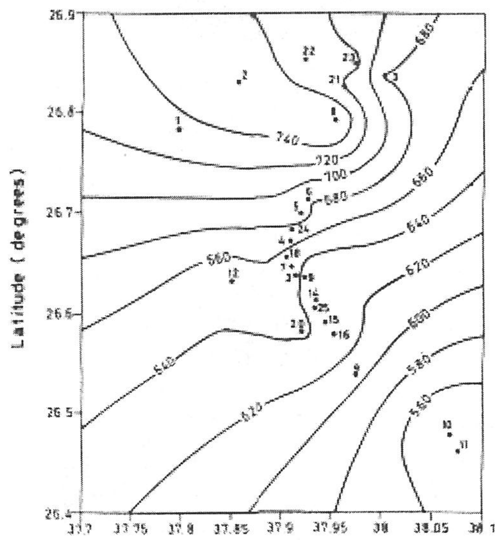

Fig. 3 Water level contour map of the Saq sandstone and the alluvial aquifer system in meters above sea level.
(Coordinates in decimal degrees)

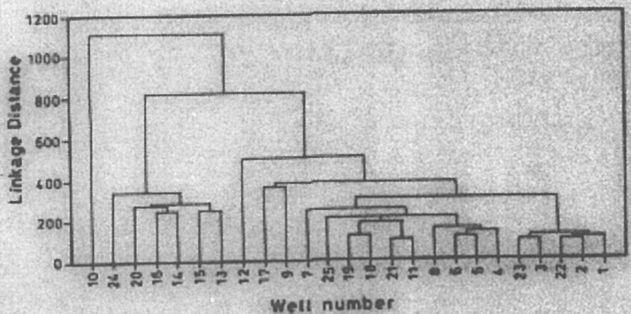

Fig. 5 Dendogram using single linkage for samples.

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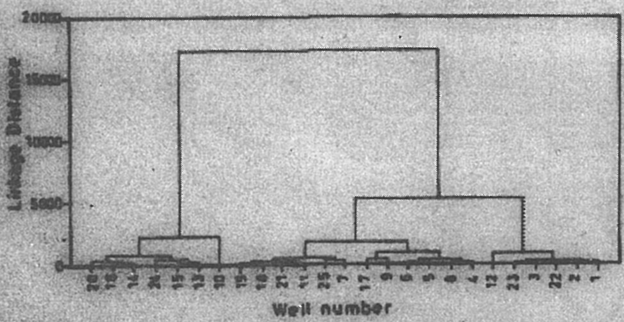

Fig. 6 Dendogram using Ward's method for samples.

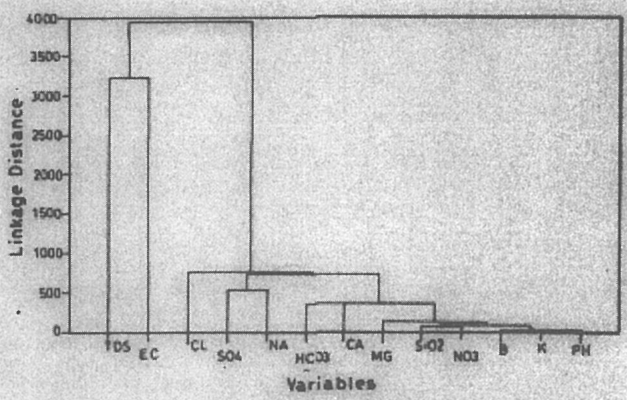

Fig. 7 Dendogram using single linkage for variables.

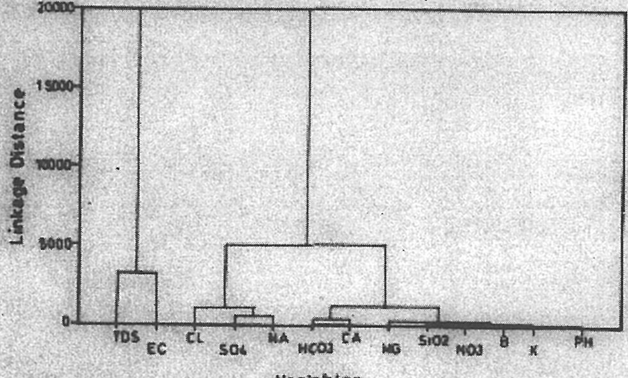

Fig. 8 Dendogram using Word's method for variables.

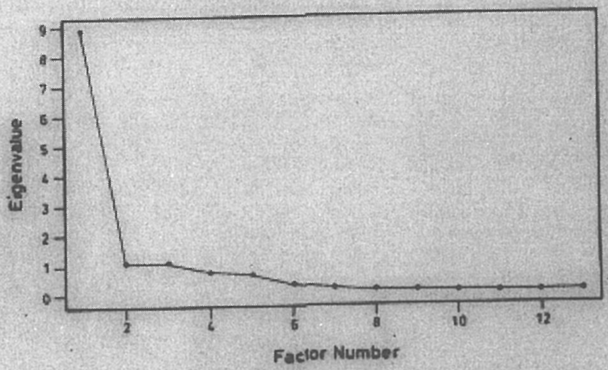

Fig. 9 Scree plot of eigenvalue and factor number.

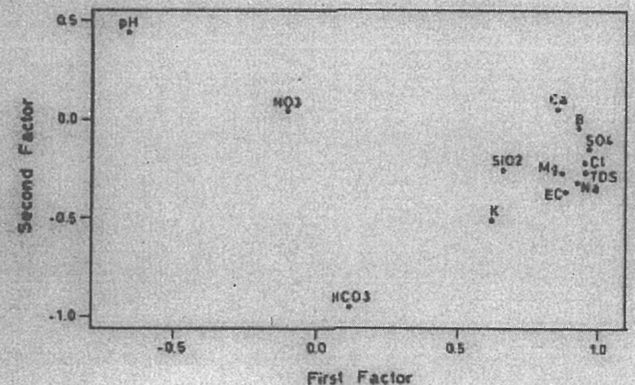

Fig. 10 Loading plot of first factor against second factor.

Saudi WaterNet: A Searchable Web-Based Database on Water Resources of Saudi Arabia

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Saudi WaterNet: A Searchable Web-based Database on Water Resources of Saudi Arabia

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Abstract

Given the scarcity of water in Saudi Arabia and the necessity for exchange of information and ideas among professionals and the public, there is a need for an effective medium of information flow. This paper outlines the design and content of a searchable web-based database on water resources in Saudi Arabia. The database includes sections on news, water resources, institutes, water experts, bibliography, policies and regulations, and links. The database can be updated, accessed, browsed, and searched with an internet browser from anywhere in the world. The internet site of the database also includes a discussion forum. The database, though in the experimental stage, was loaded for internet browsing and its design and content will be updated frequently. Once complete and available to the public, the database is expected to greatly serve the water issue in Saudi Arabia.

Key words: Water in Saudi Arabia, Hydroinformatics, Water Database

Introduction

In this critical time of water resources evaluation (or re-evaluation) in Saudi Arabia rises the great importance of not only collecting and archiving information but also making available the information to both the public and professionals.

Several governmental, semi-governmental, academic, and private entities deal with water in Saudi Arabia. They include the Ministry of Water (MOW), Universities, King Abdulaziz City for Science and Technology (KACST), Saline Water Conservation Commission (SWCC), Saudi Geological Survey (SGS), water research centers, Presidency of Meteorology and Environment (PME), and Saudi Aramco, to name a few. These organizations and many others deal directly or indirectly with one or more aspect of water such as regulations, legislations and policies, research, water supply, distribution, protection…etc. Each entity has some information on water-related issues in varying sizes, and has its own method of keeping and archiving the data, including conventional and electronic formats. Many of the listed institutions do not have a mechanism for making available the information they have either to the public or to researchers. They, probably, do not think they are obligated to share their information with others or they might not have the resources to organize and archive their data; their limited resources are directed to more compelling needs (or what is thought so). Some of the organizations probably do not realize the significance of publishing or sharing data.

Sharing and exchanging ideas is probably as important as sharing the data. Conferences, symposia, and technical meetings and seminars are good media for professionals to exchange ideas. However, there is a need for a forum that is available for larger audience and not restricted in time.

A web-based database is probably one of the best media for sharing and exchanging ideas and information. Having available a web site that has updated information on water-related issues grants a continuous and fast interaction between professionals, decision makers, and the public. In addition to serving as a source for data, the web site can be an efficient and effective means to disseminate news and announcements which will, most likely, reach more people in time than conventional ways.

Many organizations around the world have separate departments that work as data-clearing houses. Probably the best example is the Water Resources Section of United States Geological Survey (USGS) where real-time data are provided on-line through their web site at http://water.usgs.gov. Another example is the Water Information Integration and Dissemination System of the Texas Water Development Board at the site http://wiiddev.twdb.state.tx.us/ where water data can be searched and downloaded. These tow organizations have sites that are updated frequently and contain a lot of the data they collect on many hydrologic parameters such as precipitation, flow rates, water levels in wells, groundwater quality data, river discharge rates, and many others. There are other sites for organizations that do not necessarily collect their own data in the field, but get the data from different organizations and integrate, archive, and post the data on the internet. Examples on this include many of the scientific societies such as National Groundwater Association (http://www.ngwa.org), International Association of Hydrogeologists (http://www.iah.org) and the UNESCO (http://www.unesco.org/water/). The Universities Council on Water Resources (UCOWR) and Southern Illinois University, USA maintain a searchable database - Universities Water Information Network- that has information on water experts, organizations, consulting firms, graduate programs and other water-related information (http://www.uwin.siu.edu).

In this paper, a web-based searchable database on water of Saudi Arabia is suggested. This data integration and dissemination system is intended to be a reliable source of information on water resources in Saudi Arabia. The site will also contain a list of most –if not all- experts in water-related fields, and should be a good medium for disseminating information, news, and announcements. The site can be hosted and administered by one or more of the institutions working in the field of water. Because they are research-oriented, academic departments and research centers may be the suitable places to host the database.

The suggested database system includes seven basic parts: (1) water resources (2) news and announcements, (3) institutions, (4) water experts; (5) bibliography; (6) policies and regulations; and (7) links. A discussion forum is also hosted in the same web site. This system is searchable user-friendly, interactive and can be easily accessed and updated. Specifications of the database and the methodology in its design and implementation are described in the sections below.

Database Contents

Information in the database is organized in five parts that can be easily accessed and queried: news, water resources, institutions, water experts, bibliography, policies and regulations, and links (Table 1).

News

This section has postings of the latest news and announcements. This section should greatly serve the profession by keeping the readers aware of all relevant activities.

Water Resources in Saudi Arabia

This section contains collected information on the major components of the water resources in Saudi Arabia like groundwater, surface water, desalination, and reclaimed wastewater. The information can be in the form of maps, graphs, spreadsheets or other formats.

Institutions

Following this link, the reader will find a list and contact information on all institutions dealing with water in Saudi Arabia. The list will include governmental, semi-governmental agencies, academic departments and centers, and scientific organizations and societies. Private firms are included in the *links* section.

Water Experts

This section includes an exhaustive list of all professionals in Saudi Arabia working in water-related fields. Each entry on a professional has his/her name, field of interest, affiliation, and contact information. This section will be very useful, especially to scientific organizations, consulting firms, or people looking for information on any water-related topic.

Bibliography

This section contains a listing of many published literature on water in Saudi Arabia. The list follows reference citation styles and includes books, journal papers, reports, annual books, major press releases, and newspaper articles...etc. There is a field that indicates the availability of the reference to the host of the web site, in case the host decides to acquire literature. The list can be searched by author, year, title, or a key word.

Policies and Regulations

This section is dedicated to post either as links or as documents all available regulations and policies. This includes governmental policies and regulations related to water issues like pricing, water well drilling regulations and permits, water quality standards for different purposes, water conservation and protection, specifications for landfills, disposal sites and industrial discharge. Among the major sources of information on this section will be Ministry of Water, Presidency of Meteorology and Environmental, Ministry of Municipal and Rural Affairs, Ministry of Agriculture, and Saline Water Conservation Commission. Whenever ready, the National Water Plan will be included or highlighted in this section.

Links

Finally, the site will have links that we will update frequently to other sources of information on the internet that are related to water in Saudi Arabia or water in general. The section will also have links to consulting firms, offices, and companies working in water-related business like hydrogeological studies, environmental studies, desalination projects, water supply...etc.

Discussion Forum

Internet discussion forums have proven useful in providing a good quick source for expert opinion, stimulating interactive discussions among experts and between the public, experts and decision makers as well. The site has started with one general-subject non-moderated forum, which if seen necessary will be categorized and/or moderated later.

Table 1. Fields and formats of the database content.

Database	Water Resources	Institutions	Water experts	Bibliography
Fields	▪ Groundwater ▪ Surface water ▪ Desalination ▪ Waste Water	▪ Name, ▪ Location, ▪ Major activity ▪ Contact Address	▪ Name ▪ Specialty ▪ Affiliation ▪ Contact address	▪ Author ▪ Title ▪ Year ▪ Source ▪ Availabi lity
Data Formats	▪ Maps ▪ Graphs and charts ▪ Spreadsheets ▪ Other documents	Table	Table	Table

System Specifications and Design

The System users are classified into three types: Administrator, Web Master and Casual User. The system administrator can add new webmasters, and edit/delete the existing webmasters. The Web Master can easily update the site from any terminal that supports a web browser and Internet access. A user-friendly control panel is made for both Administrator and Web Master. The system provides a mechanism to classify access permission to the database.

The System was developed under Microsoft Windows2000® Operating System using Client/Server architecture. The server side environment was implemented using Internet Information Services ® (IIS.5) and Microsoft Access 2000®, and the client side was implemented using Microsoft Visual Interdev® V.7.

The system modules are better explained by using the site hierarchy and the site interfaces. Different traces of pages will show different views of the system. The interface hierarchy of admin, webmaster, and casual user of the Saudi WaterNet are shown in Figures 1, 2, and 3, respectively.

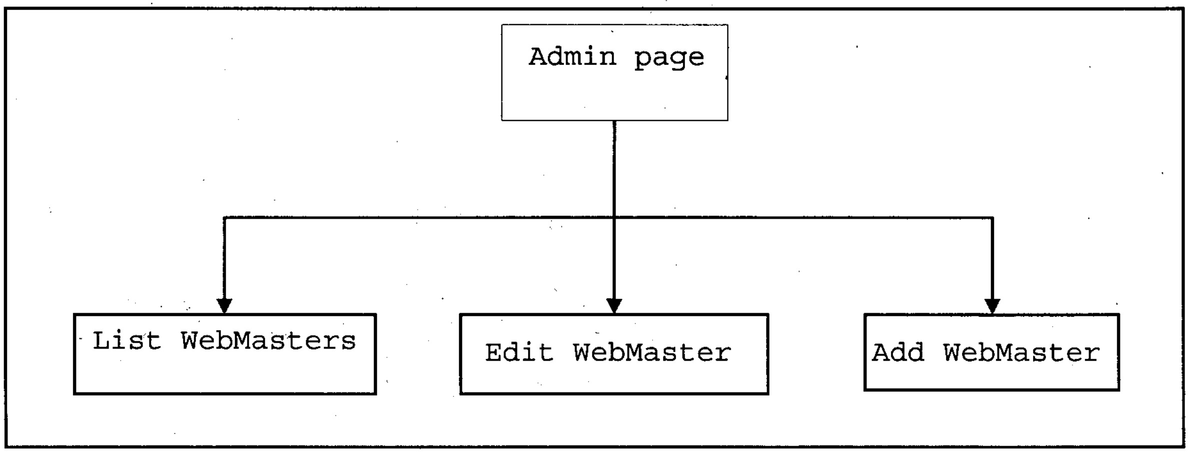

Figure 1 Admin interface hierarchy

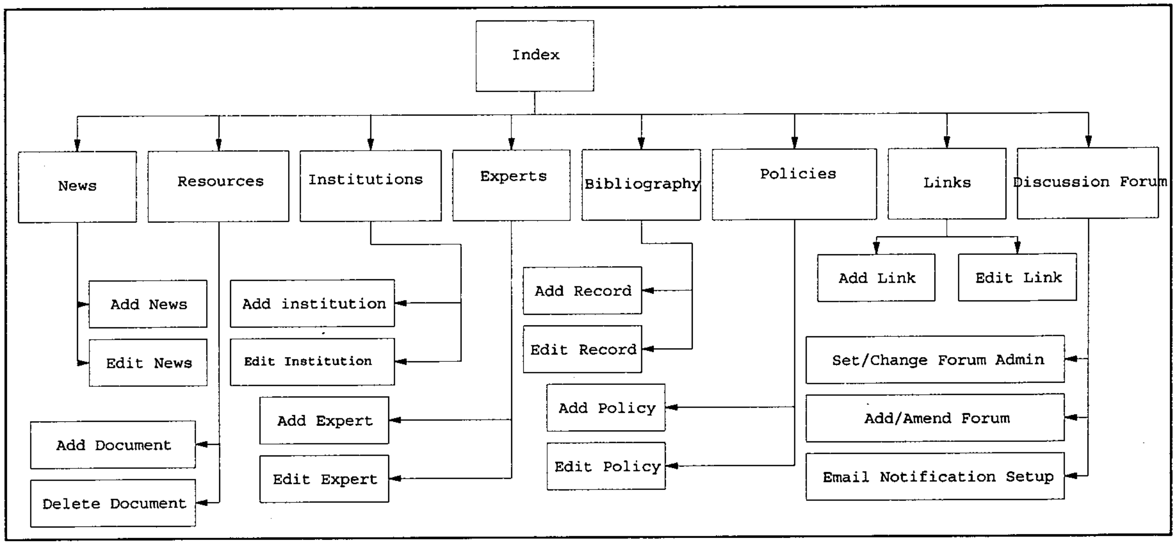

Figure 2. Webmaster interface hierarchy.

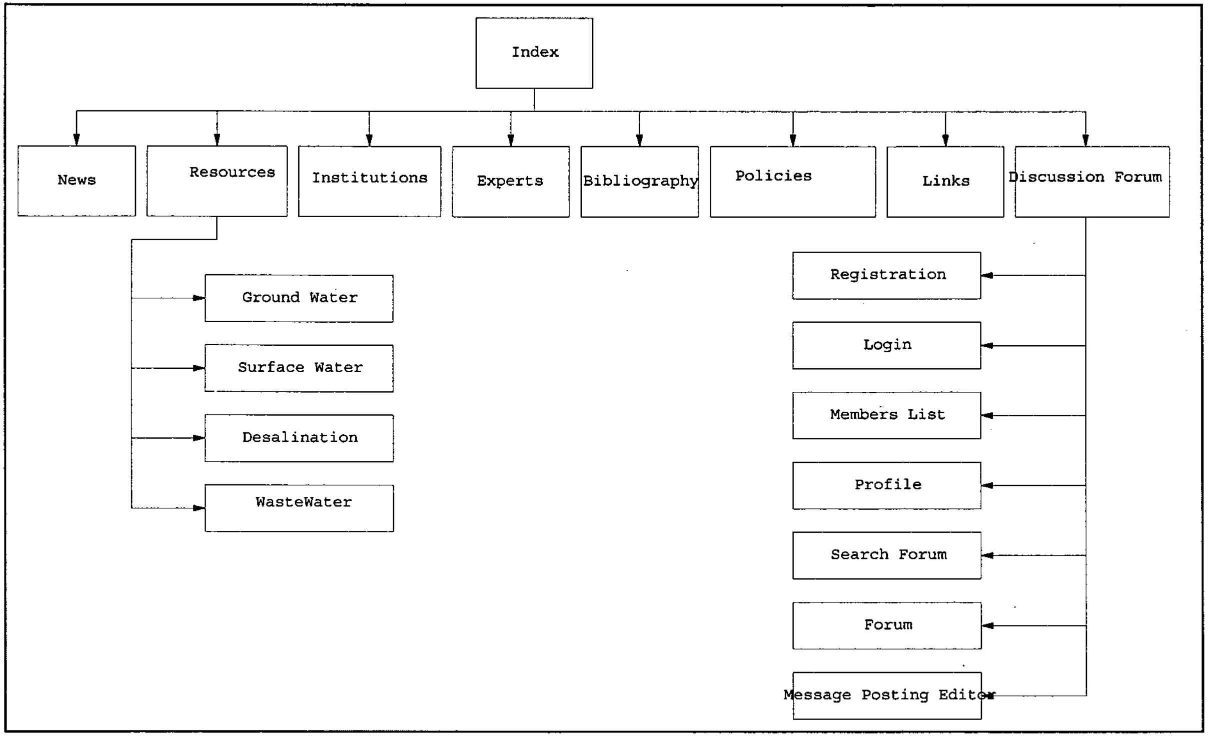

Figure 3. Casual user interface hierarchy

Status of the system

The system has been loaded for experimental purposes at the address: http://www.kfupm.edu.sa/saudiwaternet/, and is still modest in content and design. Figure 4 shows the default page of the site where the latest news and announcements are displayed. The site is being updated with more information as they become available. Most of the information currently included in the database of water resources were obtained from published literature (e.g., MOAW, 1984; Edgell, 1997, Al-Ibrahim, 1990, SWCC, 2002). The site currently contains information on about 70 experts in water-related fields with contact addresses, and 260 references in the bibliography section. Figure 5 and 6 are examples of the information in one entry of the experts section and one page of the bibliography section, respectively. The discussion forum is functional and casual users can register and post messages (Figure 7).

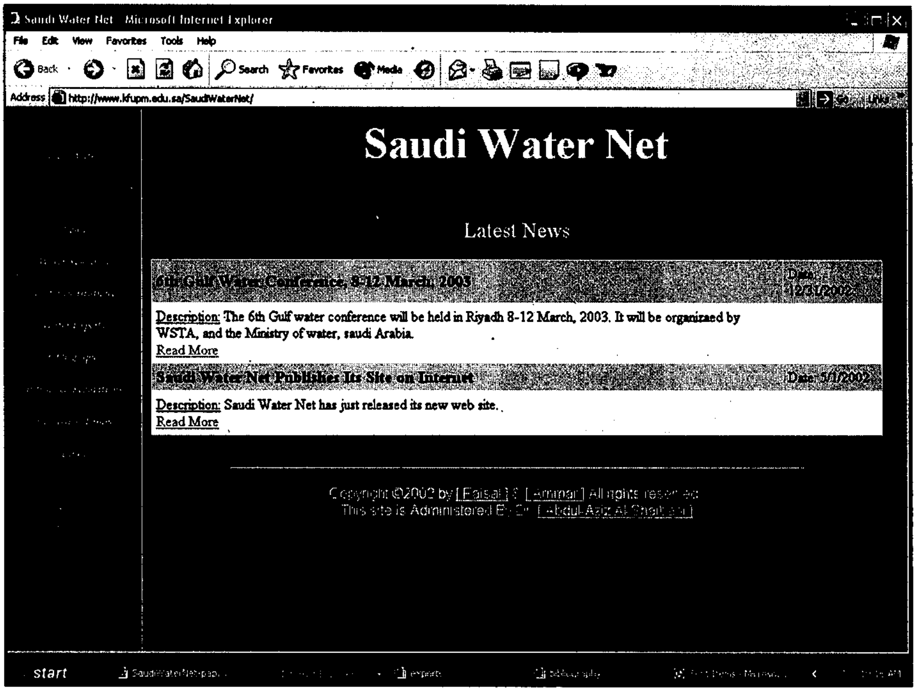

Figure 4. Default page of the site.

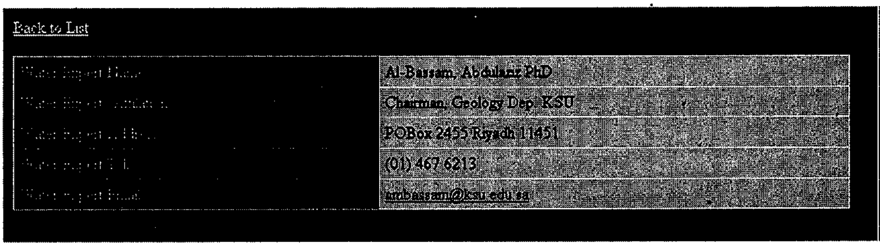

Figure 5. Expert information as viewed by a browser.

Title	Author	Details
Water Conservation Advantages fo the Individual and the Society (in Arabic)	Abu-Abat I M, and Al-Haji H M	View
Evaluation of Irrigation Water Resources in Al-Hasa, Saudi Arabia (in Arabic)	Al-Dakheel Y Y	View
Assessment of Drinking Water Quality in Riyadh City (in Arabic)	Al-Muhaideef, A A, Al-Harbi A, and Al-Sehli S	View
An Investigation into Water Saving Using Various Water Saving Devices: An Experimental Study	Al-Rumikhani Y A	View
Oil and Water Do Mix in the Case of Saudi Arabia	Al-Sahlawi M A and Choudhury M A	View

Figure 6. A sample from the bibliography section information.

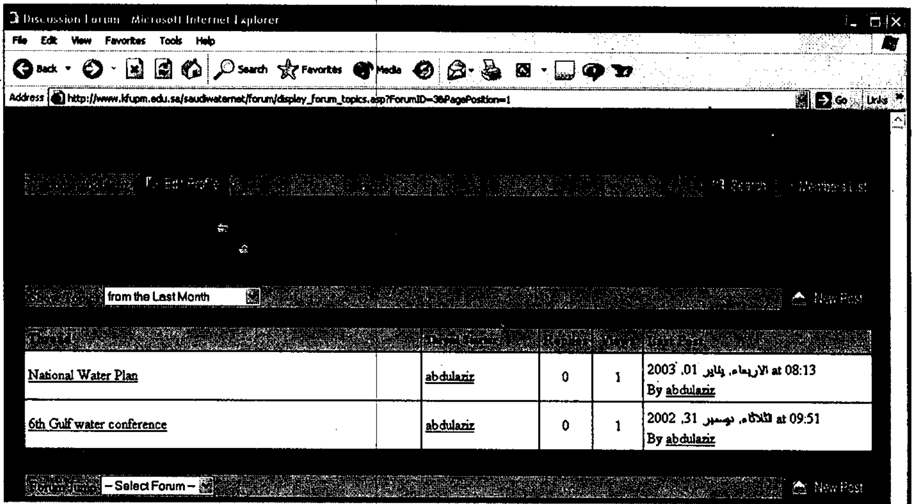

Figure 7. Default page of the discussion forum where the titles of threads are listed.

Conclusion and Recommendations

A searchable user-friendly web-based database on Water in Saudi Arabia was created. The database and the accompanying discussion forum will help in disseminating information and stimulating interaction among professionals and between professionals, decision makers and the public. Designing a web page, a database, or starting a discussion forum is not a major issue in itself. For this kind of system to be successful, two things are essential. First, governmental, academic, and private sectors need to develop effective and efficient systems of data acquisition and archiving utilizing the vast advancements in computers and information technology. The second, and probably most important requirement, is there need to be a change of attitude towards the release of water-related data. It would be better for both the profession and the water issue in Saudi Arabia if agencies that have basic information on any aspect of water resources develop mechanisms of disseminating and sharing information. Acquiring the right information means better water-related research and better informed decisions. If information exchange and dissemination has been important in the past, it is a must now given the current critical situation of water in Saudi Arabia.

Acknowledgements

The author would like to acknowledge King Fahd University of Petroleum and Minerals (KFUPM) for the support of this work. The design of the system and the site was done by Faisal Al-Mutawwa and Ammar Al-Mubaiyedh for their senior project at Information and Computer Sciences Department, KFUPM.

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Potential Surface Water Resources and flood Hazards in Wadi Baisha, Southwest Saudi Arabia

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and Mohamed Al-Zahrani (Saudi Arabia)*

Potential Surface-Water Resources and Flood Hazards in Wadi Baish, Southwest Saudi Arabia

Hussam Khiyami, Ali Al Balkhi, Saad Al Harthi, Mohammed Al Zahrani, and Amro Dahlawi

ABSTRACT

The surface water resources in south western Saudi Arabia are restricted to the intermittent flow in the wadis, which discharge their waters, usually in the form of flash flood, into the coastal area between Jeddah and Jazan. These wadis are namely; Wadi Baish, Wadi Hali, Wadi Al-Ahsebah, Wadi Yibah, Wadi Dawgah and Wadi Al-Lith.

The estimation of the runoff in these wadis will give an idea about the potential surface water resources that are yearly wasted in the coastal area and the consequent flood hazards in the downstream section. These floods commonly cause damage to properties and may result in loss of lives. The accumulation of floodwater can later be a source of disease that may affect human health. The surface water needs to be conserved and the floods need to be controlled. Engineering solutions has to be suggested and dam locations need to be recommended.

This paper considers the surface water investigation performed in Wadi Baish basin as a part of the investigations that will be performed in the other wadis. Wadi Baish basin is one of the largest basins in southwestern Saudi Arabia covering an area of approximately 5970 km^2. The wadi has only one flood gauging station in the down stream section with only 14 years of valid records. Therefore, the amount of runoff was estimated using different techniques including the morphometric analysis The results indicate that around 85 mm of the rain water will infiltrate into the ground per hour. Any excess rain will flow at a rate of 8.29 m^3/sec for every millimeter of rain. Based on this value and on the physiographic parameters, corrective measures are recommended in order to conserve the water and to mitigate the flood hazards. A numerical analysis technique using WMS software to estimate the amount of runoff is in progress.

Similar investigations are planned to cover the surface water resources and the flood hazards in the other wadis. An overall surface water management plan will be suggested for southwestern Saudi Arabia.

1. INTRODUCTION

After rainstorms, one part of the rainwater infiltrates through the ground to recharge the groundwater aquifers, another part evaporates and the rest runs off on the ground surface. Floods happen oftenly when the intensity of rainstorm is larger than the maximum capacity of surface soil to infiltrate the water. In southwestern Saudi Arabia, waters from Wadi Baish, Wadi Hali, Wadi Al-Ahsebah, Wadi Yibah, Wadi Dawgah and Wadi Al-Lith are wasted yearly in the Red Sea and also causing flood hazards in the coastal area. These wadis are not gauged and consequently amount of wasted water and the magnitude of floods are not known. Few studies were performed on the flood hazards along the coastal area in the western part of the kingdom by Sorgreah (1971), Al Shareef (1984), Abou Al Heiga (1985), Taj (1986), Dames and Moore (1988), Bazuhair and Hussein (1989), and Al Harbi (1998). The studies are not enough to find solutions to the flood hazards.The most comprehensive study was that completed on Wadi Al Lith by Al Harthi, et al. (2000). They used the Statistical Frequency Analysis of Rains method to set the necessary interpretations of the available information on floods and rains in Wadi Al-Lith. They used the Geomorphologic Instantaneous Unit Hydrograph (GIUH) method (Rodriguez-Iturbe and Valdes, 1979) to construct the floodwater flow curves. They estimated an annual runoff of 37.53 m^3/s in Mars and a range of 5 to 9 m^3/s in the other months of the year.

Wadi Baish, as an example, discharges its floodwater, usually in the form of flash floods, into the coastal area and commonly causing damage to properties and may result in a loss of one or more lives. Accumulation of floodwater can later be a source of disease that may affect human health. The wadi has only one damaged flood gauging station in the down stream section with only 14 years of valid records.

The Saudi Geological Survey initiated an investigation program to study the potential surface water resources and the flood hazards along the above mentioned wadis. This phase of the study is to predict the run off in Wadi Baish using different techniques including morphometric analysis, water budgeting and numerical modeling. This paper discusses the results of the morphometric analysis of Wadi Baish basin. The morphometric analysis technique is based on the analysis of several physiographic parameters of the basin with wide range of physical and topographical characteristics of the basin and its stream channel system. It requires the measurements of aerial aspects of the basin, linear aspects of the channel and relief (gradient) of the basin ground slopes and channel network.

Wadi Baish is one of the largest basins in southwestern Saudi Arabia covering an area of approximately 5970 km^2. Different physiographic variables in addition to rock and soil vegetation variables were measured in Wadi Baish catchment. Several parameters were suggested by Horton (1932), Snyder (1938), Langbein (1947), Johnston and Cross (1949), Strahler (1964), Gray (1965), and Chorley (1967). The physiographic parameters measured and analyzed in this study were suggested by Seyhan (1977). These parametrs were reviewed and analyzed and later used in the most appropriate equations to synthesize a unit hydrograph for Wadi Baish catchment. The results were then compared with actual runoff data obtained from the gauging station. Engineering solutions are necessary to save the wasted waters, mitigate the hazards and control the floods.

2. Catchment area characteristics

2.1 Geometry and topography

Wadi Baish which is located about 650 km south west of Jeddah, between longitudes $42^0\ 15'\ 00''$ and $43^0\ 30'\ 00''$ East, latitudes $17^0\ 00'\ 00''$ and $18^0\ 07'\ 00''$ North (Fig. 1). Table 1 gives the geometry of the basin.

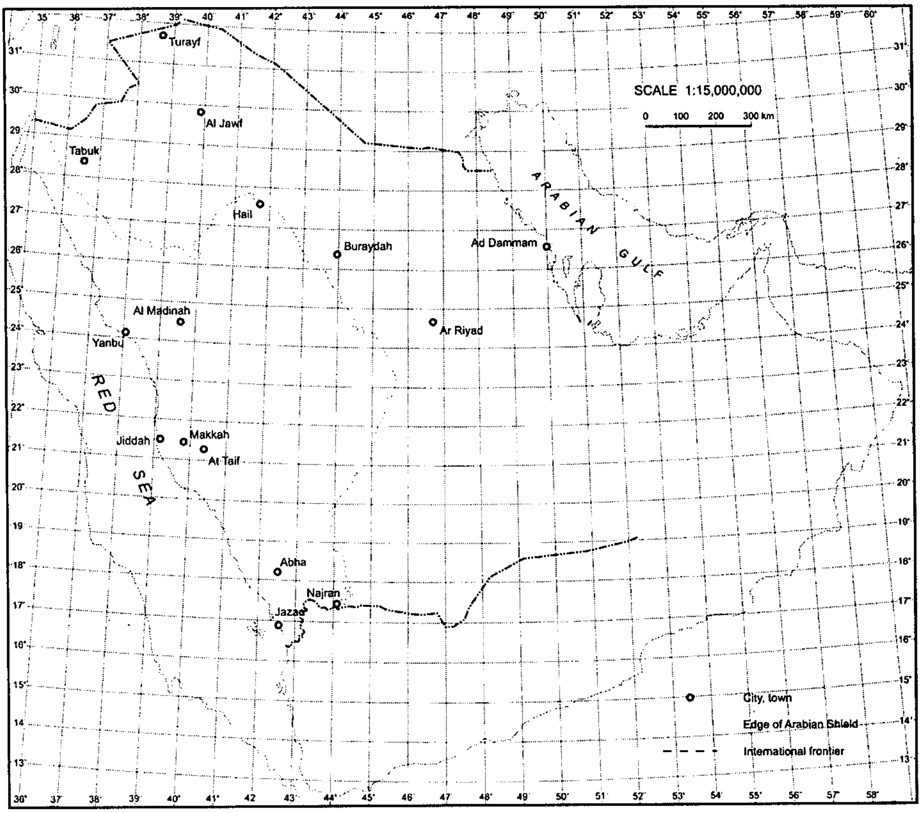


Fig.1: Location map for the study area

Table 1: Geometry of Wadi Baish basin

Parameter	Value
Watershed area	5970.22 (km^2)
Watershed length	141.62 (km)
Average Watershed width	90.39 (km)
Watershed perimeter	505.32 (km)
Elevation of the most distant point from outlet to the Watershed	3000 (m)
Vegetation area	1.4 (km^2)

The basin lies on the western slopes of the Arabian Shield draining a good sections of the escarpment mountains and Tihamat Asir hills into the Red Sea. Therefore the basin elevations range between sea level and 3,000 m above sea level (Fig. 2). The general slope of the basin is towards the southeast with slope values up to 88.2 ^{0} in the upstream sections 85.4 ^{0} in the middle sections and 25.3 ^{0} in the downstream sections.

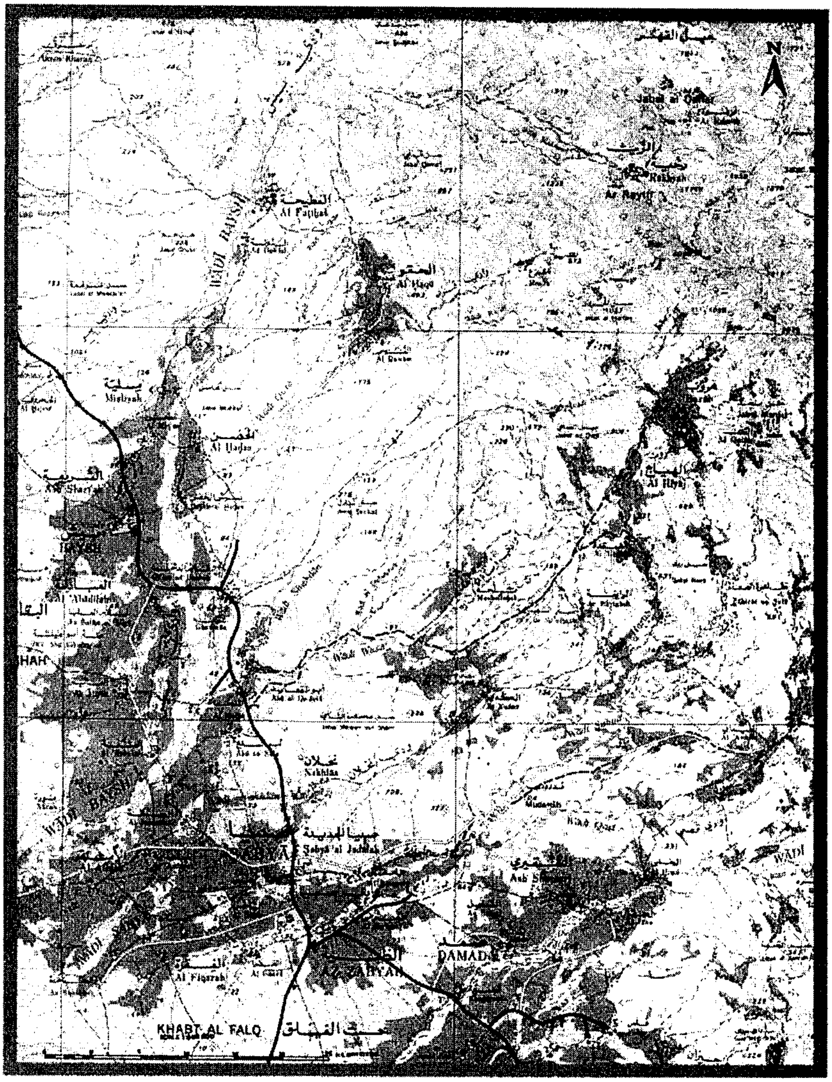


Fig.2: Topographic map for the study area

2.2 Geology

Around 85% of the basin is covered by rocks and 15% covered by soil. Most of the rock outcrops formed of Late Proterozoic volcanic and sedimentary rocks, locally intruded by plutonic rocks and partly covered by Paleozoic and Mesozoic sedimentary rocks. Tertiary to Holocene igneous and sedimentary rocks occur on the coastal plain and at several places elsewhere in wadi Baish. For the sake of the present investigation, the geological units in wadi Baish catchment were grouped into five different units of rocks and soils having similar overall hydrological properties (Fig. 3). Table 2 shows the five different rock units and the included rock formations. The different soil units were represented on the map by their geological names.

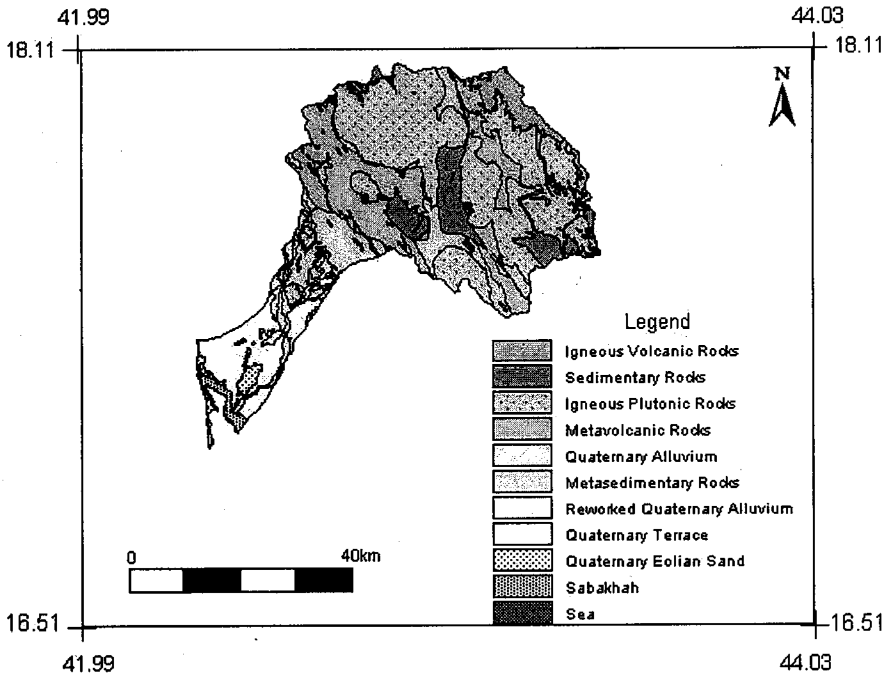


Fig. 3: Simplified Geological map for Wadi Baish Catchment

Table 2: Wadi Baish different geological units

Rock unit on the map	Rock formation included
Igneous plutonic	**Granite, Syenite, Granodiorite, Tonalite, Diorite, Pegmatite, Gabbro.**
Igneous volcanic	**Basalt.**
Metavolcanic	**Metabasalt, Metadacite, Metaandesite, Amphibolite and Sericite derived from basalt and Andesite.**
Metasedimentary	**Greywacke, Slate, Carbonaceous slate, minor Marble and Conglomerate locally converted to Biotite schist**
Sedimentary	**Wajid Sandstone, Arkosic Sandstone, Carbonate rocks**

Soil unit on the map	Soil formation included
Quaternary alluvium	**Gravel, Sand and Silt in modern channels.**
Quaternary terrace	**Inactive deposits of Gravel, Sand and Silt capped by veneer of lag Gravel.**
Quaternary reworked alluvium	**Dominately Sand and Silt adjacent to modern channels.**
Quaternary sand	**Eolian and Alluvial sand**
Quaternary sabakha	**Salt impregnated Silt with minor Sand.**

2.3 Physiography

The systematic description of the physiography of a drainage basin and its channel network required the subdivision of the basin into 54 sub-basins, the measurement of aerial aspects of these sub-basin, the linear aspects of the channels and the relief (gradient) of the basin ground and channel network. The following are the physiographic parameters measured and analyzed in this study:

1. Basin area (A)

The basin area is an important parameter so that some authors tried to use it as a sole variable to estimate the runoff. The areas of the studied sub-basins range between 27.06 to 535.9km^2 with a total area of 5970.2 km^2 for the whole basin.

2. Elongation Ratio (Re)

The elongation ratio is defined as the ratio of the diameter of a circle having the same area as the basin to the maximum basin length (Schumm, 1956). The ratio normally ranges between 0.6 to 1.0 over a wide variety of climatic and geologic terrain. Higher numbers are generally associated with very low relief whereas smaller numbers are typically indicative of strong relief and steep ground slopes. In the studied area the elongation ratio for the sub-basins ranges between 0.25 to 0.28 indicating very strong relief and very steep slopes. The overall elongation ratio of the basin is 31.81

3. Drainage Density (D)

The drainage density is an important indicator of the linear scale of the landform in a terrain eroded by streams. In general, low drainage density occurs in regions of highly resistant or highly permeable subsoil material, under dense vegetation cover and where relief is low. The drainage density in the studied sub-basins ranges between 0.1 to 0.68 km/km^2 with an average of 0.41 km/km^2.

4. Length to the center of the basin area (L_{ca})
Taylor and Schwartz (1952) found the distance from the outlet to the point nearest to the center of gravity of the basin to be a significant factor affecting the unit hydrograph lag. In the studied basin the length to the center of the sub-basin is found to range between 4.01 and 19.01 km indicating long time lags.

5. Length of the main channel (L_b)
The length of the main channel is usually dependent on the shape of the drainage basin. However, channel sinuosity does not always conferm this statement. Channel length affects to some extent the lag in the unit hydrograph as well as the magnitude of the mass transport. In the studied area, channel length ranges between 8.98 and 35.25 km indicating more or less long channels.

6. Height Difference (H)

Relief measures are indicative of the potential energy of the drainage system present. These measures are usually expressed as channel height difference (H) which is the difference in elevation between the outlet and the most distant point. The height difference measures can relate the relief to the ground and channel slopes. In the studied sub-basin, the channel height difference varies between 0.25 and 1.83km indicating a high-energy system.

7. Channel slope (S_0)

The average slope of the main channel (S_0) is an important parameter as it influences the unit hydrograph shape. The greater the slope, the smaller the time lag between the effective rain and unit hydrograph peak and also the greater the peak discharge. The average slope of the main channel in the studied basin ranges between 0.02 and 0.12.

8. Topographic factor (T)

The topographic factor, representing the basin geometry, is the ratio of the length of the mainstream (L_b) to the square root of the average channel slope (S_0). It was judged to be significant in multiple regression with basin area and measures of rainfall intensity and frequency (Potter, 1953). The topographic factor in the studied basin ranges between 26.87 and 1040.64 showing a great range of variations.

4. FLOOD ANALYSIS

4.1 Flood records

One flood measuring station existed in the downstream section of Wadi Baish at Al-Fatiha. Only 14 years of valid records are available for this station between the years 1970 - 1983 before the station was destroyed. Figure 4 shows the average flood runoff per month, which ranges from a minimum of 1.80 m^3/sec for December to a maximum of 13.07 m^3/sec for April. The flood data was used to construct a recurrence curve (Fig. 5). However, the data shows diversion from the straight-line relationship making it difficult to predict the magnitude of the 50 years flood. Therefore it was necessary to look for other procedures to predict the flood at Wadi Baish. The technique used at this stage of the investigation is the conventional synthetic unit hydrograph technique.

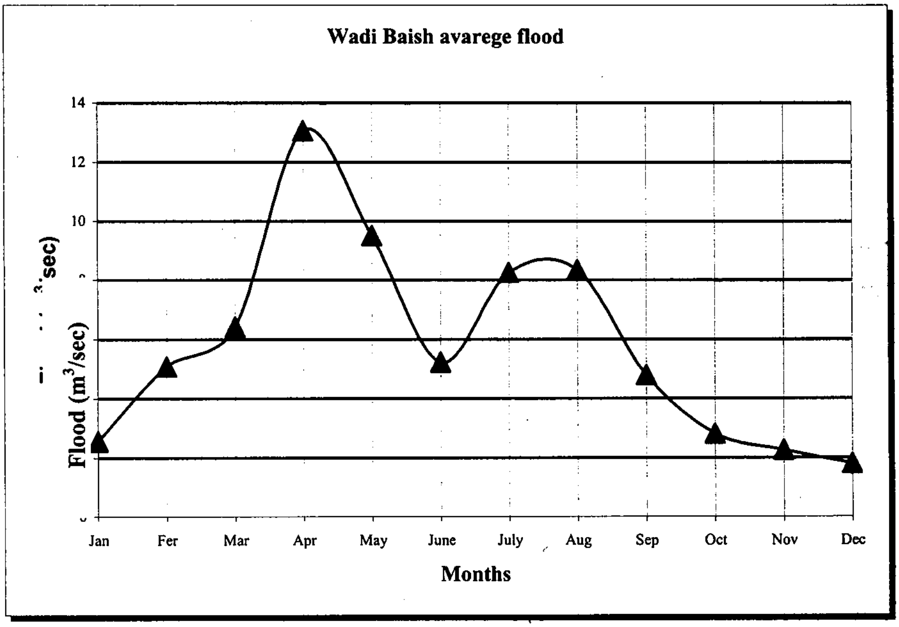
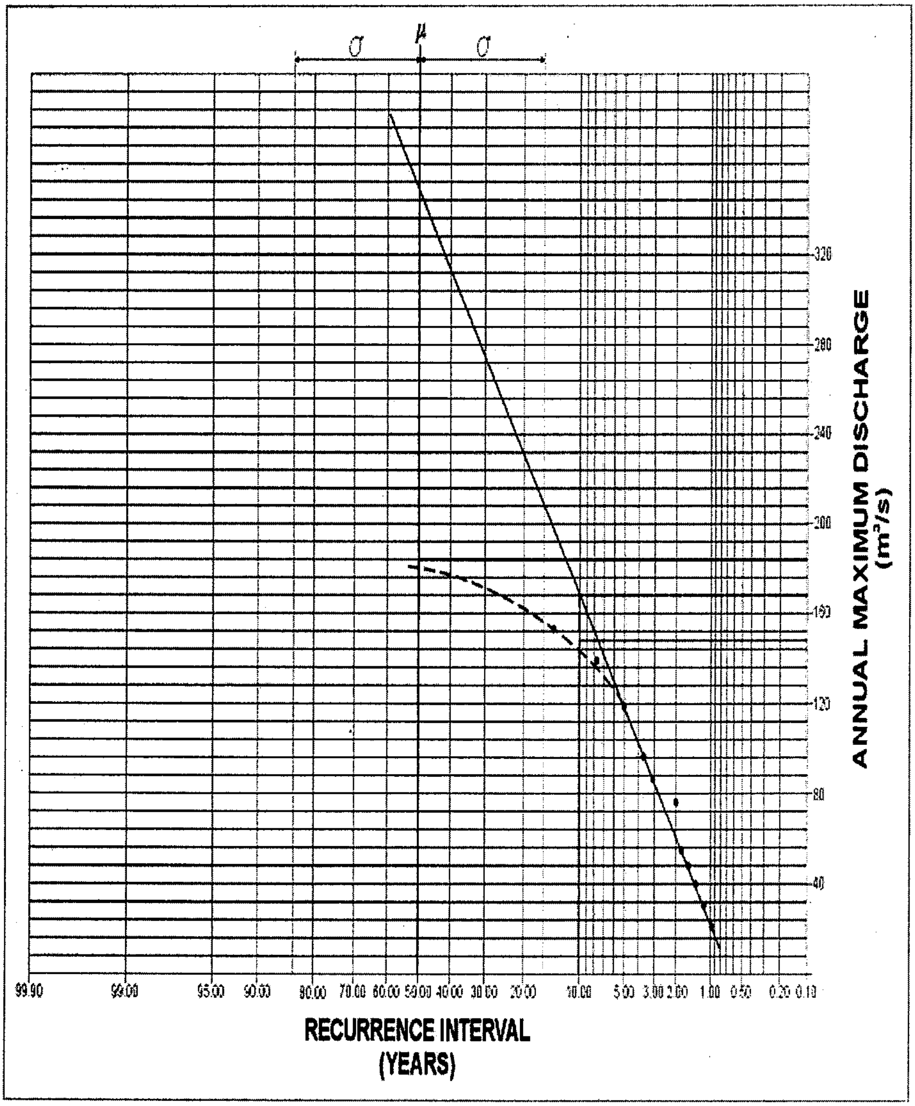


Fig. 4: Wadi Baish average flood.



σ
μ
σ
320
280
240
200
160
120
80
40
99.90
99.00
95.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
5.00
3.00
2.00
1.00
0.50
0.20
0.10
RECURRENCE INTERVAL
(YEARS)
ANNUAL MAXIMUM DISCHARGE
(m^3/s)

4.2 Synthetic unit hydrograph

Several equations were suggested to construct a synthetic unit hydrograph based on the physiographic data. The following are the most rational equations suggested by Seyhan (1977) and the ones that were used in this study.

$$t_p = 0.280(A)^{1.03}(H)^{-0.316}(L_{ca})^{-1.05}$$

$$T_p = 1.68(t_r)^{0.285}(D)^{-0.384}$$

$$T_d = 6.90(t_p)^{0.287}(t_e)^{0.200}(L_b\, L_{ca})^{0.079}$$

$$q_p = 0.032(t_p)^{-0.254}(t_e)^{-0.257}(T)^{-0.336}(R_e)^{-0.853}$$

where

t_p = lag time (hr)

T_p = peak time of unit hydrograph (hr)

T_d = duration of unit hydrograph (hr)

q_p = unit hydrograph peak discharge (m/hr)

t_r = standard duration of effective rainfall

Assumed to be equal to $t_p/4$ (hr)

t_e = duration of effective rain fall (hr)

A = watershed area (km^2)

R_e = elongation ratio

Ratio of the diameter of a circle having the same area as the basin to the maximum basin length.

D = drainage density

= Ratio between length of streams and area of watershed (km/km^2)

H = channel height difference.

= Difference in elevation between the outlet and the most distant Point (m).

T = topographic factor

= ratio between the length of the main stream (L_b)to the square root of the average channel slope (S_0).

L = length of the main channel (km)

L_{ca} = length to the center of the watershed area

= Length between the outlet and the center of gravity of the watershed (km).

Figure 6 shows the constructed unit hydrograph for Wadi Baish. It indicates that every millimeter of effective rainfall on Wadi Baish results in a peak flow of 8.29 m^3/s at Al-Fatiha station

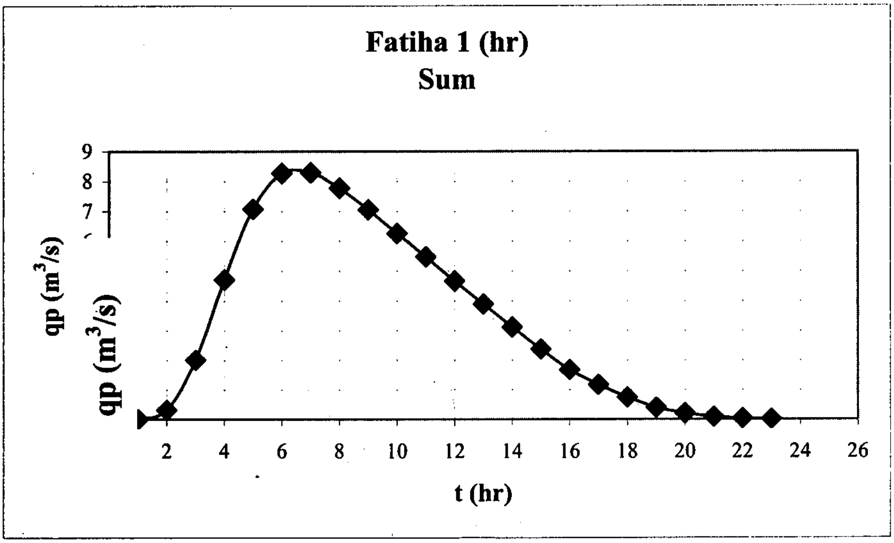


Fig.6: Synthetic unit hydrograph (Al-Fatiha - Wadi Baish)

4.3 Effective rainfall

Parts of the rainwater falling on the ground may infiltrate, evaporate or used by the plants. The rest, which is the effective rainfall, will runoff. Therefore, in order to calculate the effective rainfall, the magnitude of infiltration, evaporation, and transpiration should be measured or estimated for the basin.

No records of evaporation measurements could be obtained from any meteorological station in wadi Baish or in the nearby areas. However, the Water Atlas of Saudi Arabia (Ministry of Agriculture and Water, 1984) indicates that the rate of evaporation in Wadi Baish ranges between 8 and 12 mm/day or 0.3 to 0.5 mm/hr, a value that can be ignored. The plants cover 1.4 km^2 (Table 1) or 0.02% of the total area of the basin. Accordingly, the amount of water taken and transpired by the plants can also be ignored. By ignoring the values of evaporation and transpiration in the flood analysis adds a factor of safety to the flood calculations.

Several infiltration tests using a double ring infiltrometer (Johnson, 1963) were conducted on the different rock and soil units. Figure 7 shows a generalized infiltration curve for the rock units upstream of Al-Fatiha flood measuring station. The average infiltration rate is 85 mm/hr

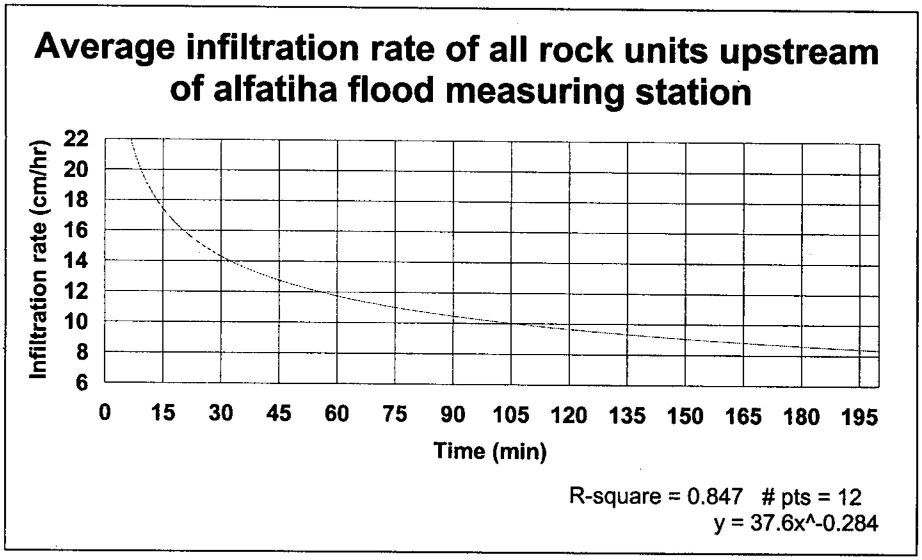


Fig. 7: Generalized infiltration curve for the rock units upstream of Al-Fatiha

4.4 Flood estimations

Wadi Baish basin receives large quantities of rainwater that in many times, exceed the capacity of the basin. In April it receives an average of 821 mm while in the other months of the year it receives between 129 and 580 mm. The absence of hourly rainfall records in wadi Baish prevented the proper utilization of the constructed synthetic unit hydrograph. However, it can be stated from the available information that approximately 85 mm of the rainstorm water per hour will be lost by infiltration through the ground and the rest will flow at a rate of 8.29 m^3/s for every millimeter of excess rain. The infiltrated water will recharge the groundwater in the basin and may tend to add to the flood through base-flow in the downstream sections.

A numerical analysis technique using WMS software to estimate the amount of runoff is in progress. Similar investigations are planned to cover the surface water resources and the flood hazards in the other wadis. An overall surface water management plan will be suggested for southwestern Saudi Arabia.

5. REMEDIAL MEASURES

Since the nature of the basin area is characterized by irregular down sloping in many of its parts, it is necessary to convert the rainwater from an environmental hazard, in the form of destructive flash floods that threatens life and property of the inhabitants of the area, to a water source that feeds aquifers and reclaim land for agricultural purpose. Recurrent flash floods in the region were and are still causing the occurrence of a group of environmental and natural problems such as the formation of ponds and swamps, the destruction of roads and buildings, the disruption of public services, the increase of the costs of building and construction, and the loss of human life.

Accordingly the construction of a flood control dam in the downstream section of the wadi will conserve water and mitigate the hazard. Further investigations are required to select the best site for the dam and to recommend the most suitable dam type.

6. CONCLUSIONS

Wadi Baish highlands receives high annual amount of precipitation usually at high intensity, which causes destructive floods. The available hydrological and climatic data of the region are insufficient to measure or exactly predict the magnitude of floods. A synthetic unit hydrograph could be constructed using the morphometric analysis of the basin. The results indicate that for every millimeter of effective rainfall, a flood will occur at a rate of 8.29 m^3/sec at Al-Fatiha. The rainfall data should be corrected by subtracting the evaporation, transpiration and infiltration in order to get the effective rain. It was found that both evaporation and transpiration could be ignored for the wadi. However the infiltration rate amounts to an average of 85 mm/hr.

7. RECOMMENDATIONS

Until a permanent remedial measure is established, the following steps are recommended:

1. Repairing the flood measurement station in the wadi and follow up of periodic maintenance of the station.
2. Establish modern metrological stations as this study and its results depend on the information and measurements provided by those stations.
3. Keep residential areas and civil constructions out of the flood prone areas.
4. Establish a flood-hazard awareness program and educate the residents of the hazards of flash floods and the proper responses to it.

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Rainfall-Runoff-Erosion Model for Semi-arid catchments using GIS- A Case Study Wadi Surdud Catchment, Republic of Yemen

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Rainfall-Runoff Erosion Model for semi-arid catchments using GIS

(A Case Study Wadi Surdud Catchment, Republic of Yemen)

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Abstract

A mathematical "Sediment Yield" model has been developed and integrated with Rainfall-Runoff Model *NAXOS* [1] for estimating upland delivery rates of individual storm resulting from rainfall and runoff at the outlet of the catchment area of Wadi Surdud (2370 km^2), Tihama, Yemen.

The erosion and sedimentation processes of the upland watersheds have to be assessed by means which do not rely on historical storm flow data. Methods that depend on available or measurable representative data were developed for a deterministic approach of the erosion process. Considering the present state of knowledge of the system analysis, *GIS* techniques offer a unique opportunity for the appraisal of the complex interactions of erosion and sedimentation factors (rainfall, runoff, watershed, physical and land use characteristics) as well as sediment load contributions of the upland watershed. To apply the model, the watershed is divided into 242 subwatersheds using *TOPAZ* (Topographic Parameterization) [2]. Sediment yield is computed for each of 242 sub-basins using a steady state Sediment Continuity Equation [3] by routing mobilized sediment through a series of linear reservoir [5]. The Model uses a mass balance equation to compute sediment transport, erosion and deposition over the land surface as direct throughfall, leaf drainage and streamflow. Sediment transport is considered as the erosion rate in the plane reduced by the deposition rate within the reach. The erosion occurs due to raindrop impact as well as surface shear. The model may serve as a tool for design of soil conservation measures. The following results were obtained:

- Identification of hazard areas for soil erosion,
- Assessment of sediment transport at a given point within the basin,
- The basis for planning of soil conservation measures.

Keywords: erosion modeling; wadi Surdud; sediment yield, GIS

Introduction

Accelerated erosion decreases the area of arable land and its productivity year after year. The result is insufficient food production and, as a consequence, associated socio-economic consequences are becoming more critical throughout vast areas of the world. Arid and semiarid regions have a potential for generating and transporting large quantities of sediment mainly due to the torrential rainfall, excessive weathering, almost total lack of natural protection against detachment of soil due sparse vegetative cover providing readily available material to be eroded by runoff, and increased biotic interference [4],[5]. All these problems are related to the process of soil erosion by surface runoff in a catchment. The bulk of the eroded material is deposited at intermediate locations if the surface runoff cannot sustain transport. Moreover, some of the sediments eroded from the source can reach the river. The potential for surface soil erosion in the mountainous regions in Yemen is extremely high because of steep topography, high rainfall intensity, shallow soil, and poor land use practices.

Existing soil erosion models are requiring a large set of input parameters. Therefore, an operational model with high spatial and temporal resolution was required for the transport processes of eroded soil following individual storm events in large agricultural catchments with arid and semi-arid environments. A physical passed model is a suitable model for the appraisal of the complex interactions between erosion and sedimentation causative factors (rainfall, runoff and watershed physical and land use characteristics) and sediment contributions of upland watersheds. Such this prediction model is highly beneficial as design tools for developing alternative plans to control upland soil loss.

The objectives of this study are to: .

- Formulate a physically based storm sediment production model.
- Test this model for a big upland watershed in Yemen.
- Identify critical model parameter and relate them to some measurable watershed characteristics; and
- Identify information and data needs to evaluate management effect on soil erosion and sediment delivery.

General Characteristics of the Study Area

Location

Wadi Surdud (2370 km^2), is situated between 14° 58′-15° 35′ N and 43° 20′-43° 58′ E. on the so-called Western Escarpment of the highlands along western part of the Yemen Republic (Fig.1). It is one of seven major wadis which develop in these highlands and flow westwards to the red sea across the semi-arid coastal plain locally known as the Tihama.

Topography, Geology, and Land use

The area is comprises a gently sloping mountainous (foothills zone) at low elevations bounded from the higher rugged and highly dissected mountains that reach elevations wall over 3000 meters. The stream length and gradient of the study area are 80 km and 0.003 m/m, respectively. The main wadi channels have a mean depth of 2.0 m and width of 30 m. Surficial geology is dominated by Tertiary Yemeni Volcanic and Tawilah Sandstone in the upper catchment of the study area. Further downstream Tertiary granite intrusions cover large areas, within a short distance from the Tihama Plain. Forty two percent of the study area is mountainous terraced terrain with shallow soil depths varying from 1.5 to 3m. The rest of the study area is a rugged terrain with minor vegetations [Foto.1].

Rainfall and Evaporation

Two rainy seasons can be distinguished in the study area: one in spring, the other in summer, with 45% of rainfall occurring during July and August. Annual precipitation ranges from 450 mm in the mountain to 300 mm at the outlet of the study area in Faj Al-Hussain. The number of rainy days (>10 mm) is around 17 typical of desert climate. The rainy events are characterized by a rapid onset and high intensity short duration. Shower Storm are infrequent, localized, and variable within the basin. Potential evaportransporation [ET_O] exceeds the monthly and annual rainfall amounts observed. Calculated [ET_O] according to the Penman method is around 1825 mm/year. Groundwater abstraction and the annual recharge are estimated at 165 Mm^3/year and 96.5 Mm^3/year, respectively [6].

Field Investigations

In Wadis, turbulent mixing is sufficient to produce a homogeneous distribution of solute concentration in the cross-section. Consequently, the task of collecting a representative water sample for a laboratory analysis is generally considerably simpler than in the case of suspended sediment, where concentration my vary markedly. Nevertheless, a number of workers have encountered variations in solute concentrations in the cross-sections, particularly downstream of tributary confluences, and surveys should be undertaken at different flow levels to ensure that homogeneity exists at the measuring site.

In this work, Runoff and Sediment measurements are based on 2 stream gauging stations, which are located at the outlet of the study area and 10 rainfall gauging stations inside the catchment (Fig.2). Stage heights were measured at each station in the stream during the flow, and discharge calculated by the rating curve method. The first water samples for sediment concentrations were collected when the flow began, with subsequent samples collected at times when there were significant changes in the flow discharge (Fig. 3).

Model Description

Sediment movement down slope obeys the principle of the continuity of mass expressed by [3]:

$$\frac{\delta q_s}{\delta x} = D_r + D_i, \qquad (1)$$

where q_s (kg s^{-1} m^{-1}) is sediment transport load per unit width, x (m) is distance down slope, D_r (kg s^{-1} m^{-2}) is rill erosion or deposition rate and D_i (kg s^{-1} m^{-2}) is sediment delivered to the rill from interrill areas. The $\delta q_s / \delta x$ term represent the change in sediment flow rate along the slope.

The rate of sediment detachment by shear stress D_r (kg m^{-2} s^{-1}) is obtained from the relationship [7]:

$$D_r = K_r \tau^{1.5} \quad (2)$$

where K_r (kg m $N^{-1.5}s^{-1}$) is a soil detachability factor for shear stress, and τ (Nm^2) is the effective shear stress, which is given by:

$$\tau = \gamma . h S_f \quad (3)$$

where γ (N m^{-3}) is the specific weight of water; h (m) is the flow depth, and S_f is the friction slope. The rate of sediment detachment by rainfall impact D_i (kg m^{-2} s^{-1}) is obtained from the relationship:

$$D_i = K_s I Q \quad (4)$$

in which K_s (kg s m^{-4}) is the soil detachability parameter, I (m s^{-1}) is the rainfall intensity, and Q (m s^{-1}) is the effective rainfall.

The sediment flux Φ (kg m^{-2} s^{-1}) to the flow is written as:

$$\Phi = D_r + D_i \quad (5)$$

The sediment transport capacity is based in part on Yalin equation [8], modified by Beasley [9], which is considered to be one of the best transport capacity equation [10]:

$$T_c = 161 Sq^{0.5} \quad \textit{if } q \le 0.046\ m^2/min. \quad (6)$$

$$T_c = 16320 Sq^{2} \quad \textit{if } q > 0.046\ m^2/min. \quad (7)$$

where q (m^3 s^{-1} m^{-1}) is the flow rate per unit width, S (%) is the slope steepness.

The flow depth is estimated by Manning's equation as:

$$h = (qnS^{-0.5})^{0.6} \quad (8)$$

where h (m) is overland flow depth, q (m^3 s^{-1} m^{-1}) is flow discharge per unit width, n is Manning's roughness and is equal to 0.046(for moderate vegetative cover and rough surface/depressions of 10 to 15 cm depth, a moderate value) [11], and S is the friction slope equal to the plane slope.

The infiltration process is calculated as follows based on the Soil Conservation Service (*SCS*) method [12]:

$$F = (P - I_a) - Q \qquad (9)$$

where F (mm) is the infiltration, P (mm) is the precipitation, I_a (mm) is the initial abstraction, and Q (mm) is the actual runoff. The initial abstraction consists mainly of interception, infiltration, and surface storage, and is related to potential maximum retention as follows:

$$I_a = 0.2S \qquad (10)$$

where S_{CN} (mm) is the potential maximum retention parameter, given by the relationship:

$$S_{CN} = \frac{25400}{CN} - 25.4 \qquad (11)$$

Where CN (-) is the runoff curve number. Curve number tables may be obtained from a number of sources. To illustrate, for $CN = 100$, $S_{CN} = 0$; and for $CN = 1$, S $S_{CN} = 25146$ mm. Therefore, the catchment's capability for rainfall abstraction is inversely proportional to the runoff curve number. For $CN = 100$, no abstraction is possible, with runoff being equal to total rainfall. On the other hand, for $CN = 1$ practically all rainfall would be abstracted with runoff being reduced to zero.

The above formulations represent the groundwork for the present direction of such modeling techniques whereby the watershed is subdivided into subcatchment. Overland flow and sediment are routed along the land surface and then through the main channel by using the concept of linear storage [9]. Geographic Information System (*GIS*) are becoming more widely used in spatial hydrologic modeling. *GIS* techniques normally integrated with hydrologic and hydraulic models to quickly assemble model input data and store model output for analysis and display [13]. To apply the model, the watershed is subdivided into 242 subwatershed (Fig.4) by using *TOPAZ* (Topographic Parameterization) [2]. Sediment yield is computed for each of 242 sub-basins using a steady state Sediment Continuity Equation [3] by routing mobilized sediment through a series of linear reservoir.

In this study, a distributed parameter sediment delivery model is derived and linked with *GIS* to predict the spatial sediment delivery within an arid zone drainage basin for the identification of vulnerable areas to use in planning and designing soil conservation systems. The results can also be used with a Digital Elevation Model (*DEM*) (Fig.5) to display distributed parameter model results [14]. The *ARC/VIEW GIS* software was employed to process and analyze the necessary input data. Data layers consist of:

- A topographic map of the study area at 1:25,000 scale. Every 20 m contour was digitized and interpolated to a continuous elevation map. Slopes were derived from the *DEM* and *TOPAZ* (Topographic Parameterization). The drainage network was generated from the topographic sheet (of 1986) and the high order river course systems were updated from Landsat imagery (of 1996).
- Soil map of the study area at 1:250,000, using Landsate mapped image acquired on 1996. The maximum vegetation cover occurs between June and August, which falls in the second of the rainy season.
- An aerial photograph on 1:25,000 scale were used in combination with the field survey to produce a land use map of the study drainage basin.

Model parameters

The parameters required for this model are:

- The Curve Number (*CN*), assumed as 68 based on the measurements in the stream gauging stations at the outlet.
- The Manning friction factor (n) of flow resistance, assumed as 0.03 for planes and 0.04 for the wadi bed based on visual inspection of the wadi bed near the records and a comparison with either photographs of river with known roughness or tables which describe roughness coefficients,

- The soil detachability factor for shear stress (K_r), equal to 2.8 (kg m $N^{-1.5}s^{-1}$),
- The soil detachability parameter (K_s) equal to 6.2 (kg m $N^{-1.5}s^{-1}$),
- The specific weight of water (ρ_w) as 9779 Nm^{-3}, and the specific weight of sediment (ρ_s) as 25914250 Nm^{-3}.

Modal Application and Evaluation

The model parameters which have to be calibrate are:

- The Curve Number (*CN*),
- The Manning friction factor (n),

- The soil detachability factor for shear stress (K_r).

The ability of the model to predict sediment yield for the selected test storms is evaluated. The three parameters were assigned as described previously. A comparison of observed and predicted sediment yield shows a good agreement (Fig. 7). With a coefficient of determination of 0.93, the predicted and observed sediment delivery relationship was:

$$q_s = 1.59q_s - 0.033 \qquad (11)$$

Where q_s (kg/s) is predicted sediment transport and q_s (kg/s) is observed sediment delivery. For the model verification, the relative error in the predicted sediment transport (e_s) was calculated by the relation:

$$e_s = \frac{(q'_s - q_s)}{q_s} \qquad (12)$$

The average e_s was found to be 10.1%, the maximum was 20.6% and the minimum was only 5.5%.

The sediment delivery model (Eq.11) in conjunction with GIS has a capability to predict the spatial variability of sediment delivery of individual storm within a drainage basin (Fig. 6). Such information is useful in the identification of vulnerable areas within a drainage basin [4].

Conclusions

The developed model should have the ability to simulate and predict suspended sediment yield and sediment transport process in watershed systems, based on the hydrological and the watershed characteristics. Using the model, it is possible to calculate the effects of land use changes and soil conservation scenarios. The coupling of *GIS* technique which rainfall-runoff-erosion models has created a powerful tool for the management of soil and water resources. By using Digital Elevation Model (*DEM*), the developed model gives an understanding of the spatial and temporal distribution of runoff and erosion within a catchment during an individual storm. Factors influencing erosion include Curve Number (*CN*), Manning friction factor (n), soil detachability factor for shear stress (K_r).

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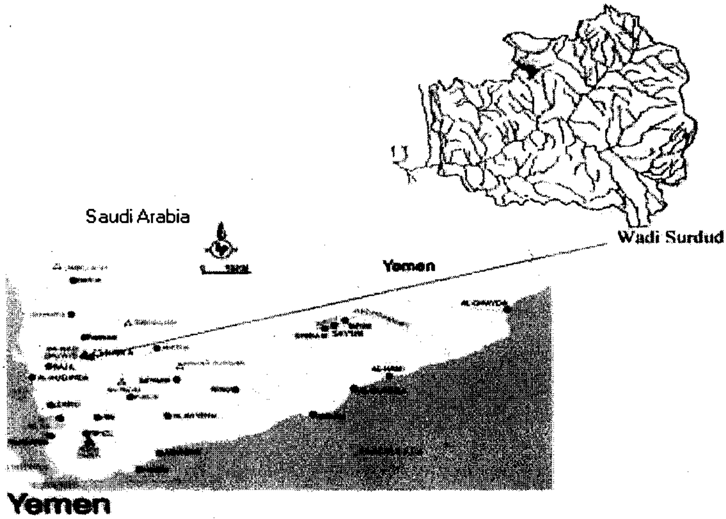

Fig.1 Location of the wadi Surdud catchment

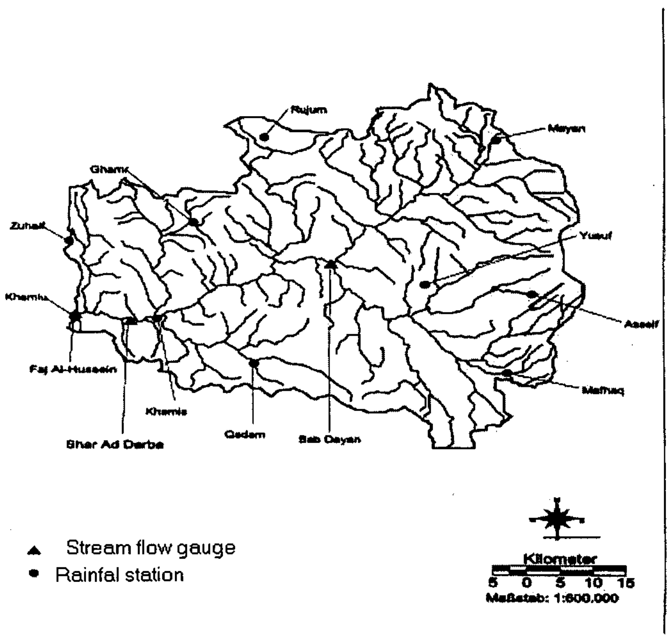

Fig. 2 Location of the gauging stations in the catchment area

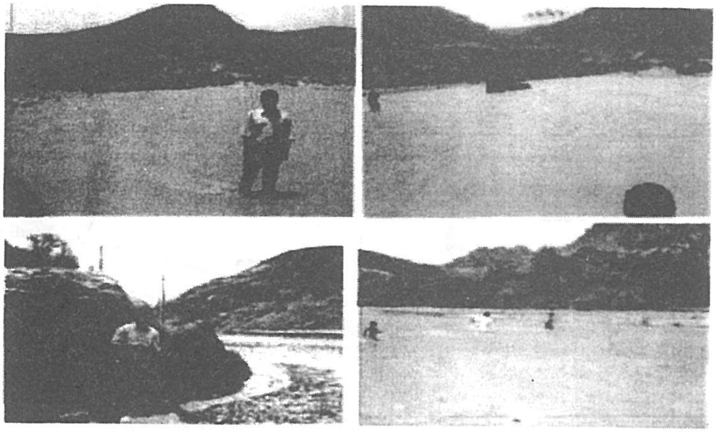

Fig3. Sediment measurements during the flood at the outlet of the catchment

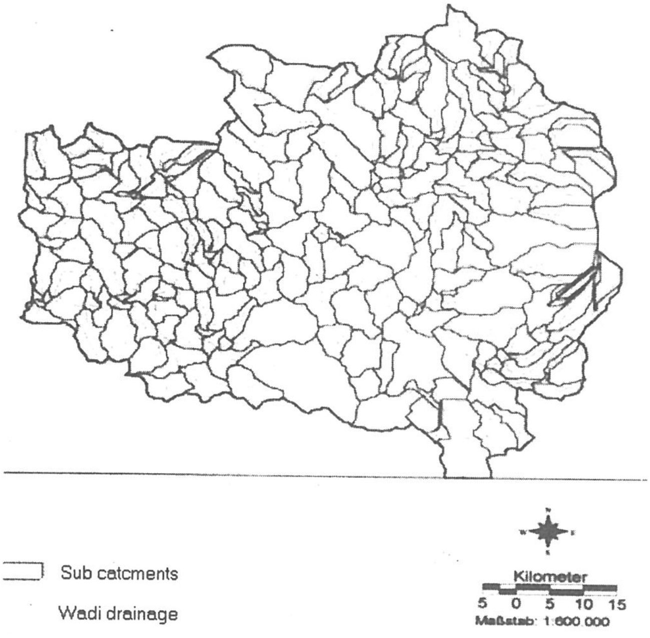

Fig.4 Wadi Surdud catchment divided into 242 sub-basins.

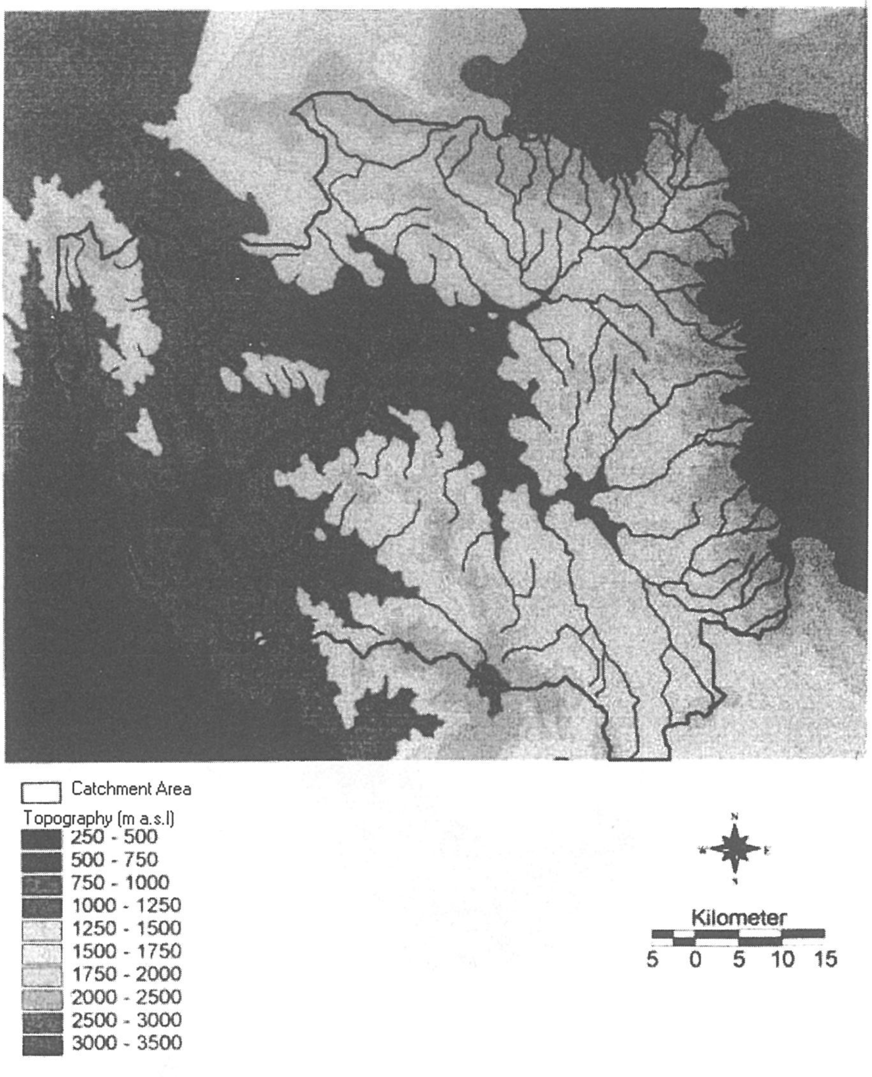

Fig.5 Digital Elevation Map (DEM) for the Wadi Surdud Catchments.

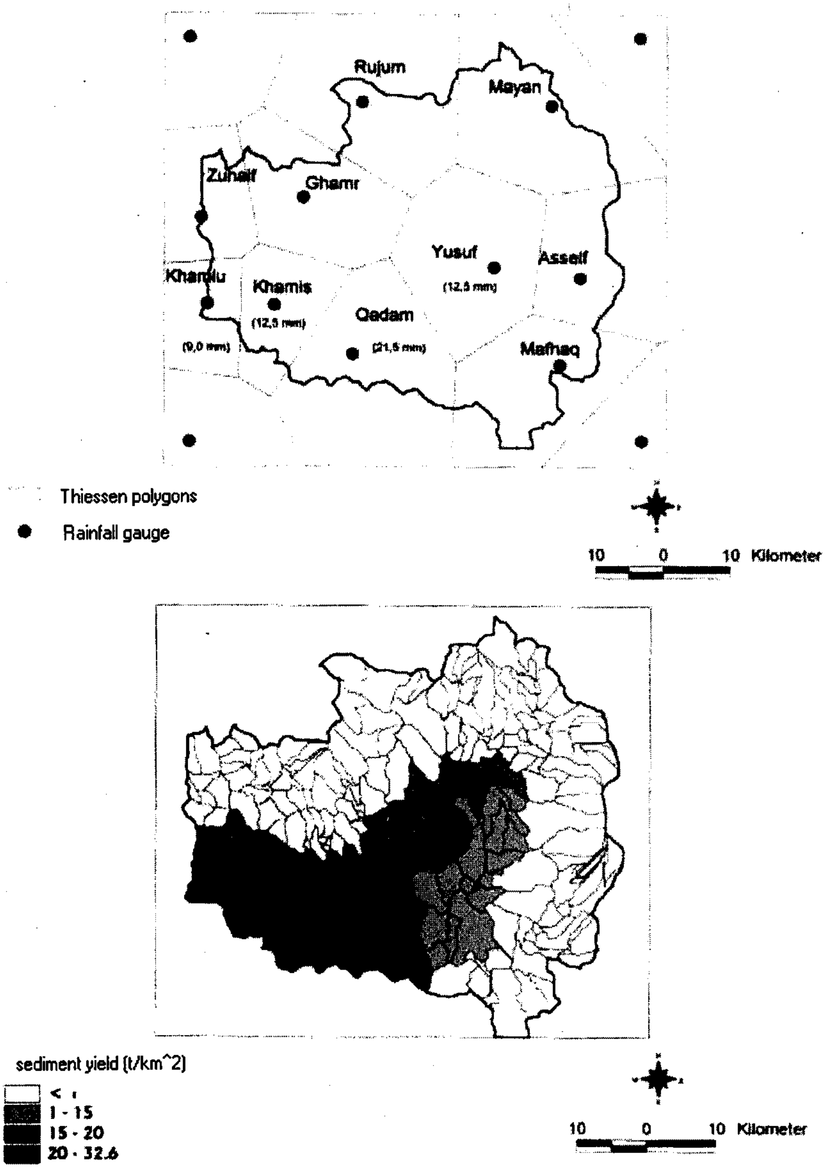

Fig.6 Simulated suspended sediment load for the storm of 05.09.1998.

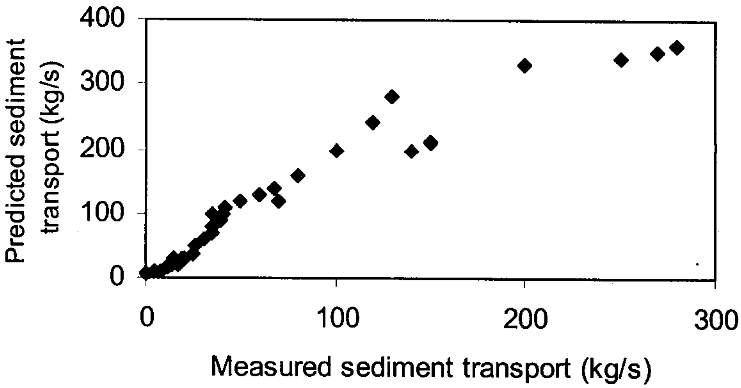

Fig.7 Measured *vs*. predicted sediment transport in the wadi surdud catchment

Remediation of Urban Groundwater Through Wastewater Recharge: A Case Study

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REMEDIATION OF URBAN GROUNDWATER THROUGH WASTEWATER RECHARGE: A CASE STUDY

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ABSTRACT

In the past 30 years or so, the Kingdom of Saudi Arabia has undergone massive urbanization and agricultural development, both of which require large volumes of water. In the case of the former, approximately 54% of the supply is from desalination plants, sometimes situated as far away as 500 km from the city (in the case of the city of Riyadh). In the case of the latter, the water supply is from depleting water tables throughout the Kingdom. As a direct result of this urbanization and development, it would be fair to state that the shallow groundwater aquifers in many parts of the Kingdom has been polluted. This is certainly true in many urban dwellings, where large volumes of municipal wastewater are generated, and in regions where wastewater is indiscriminately discharged into the desert.
The rise in water table in the cities have been attributed to a number of contributing factors such as: (1) infiltration of irrigated water; (2) leakage from water supply/foul sewage lines; (3) overflow from septic tanks; (4) natural recharge; and (5) movement of groundwater from other areas. Because of these factors and indiscriminate discharge of pollutants not meeting effluent standards, the groundwater in the cities of the Kingdom have been polluted.
In-situ remediation of the groundwater environment is time consuming, difficult and expensive. Draining this polluted water through existing drainage systems and treating this water and recharging an aquifer in the vicinity of cities would be an attractive proposition, not only from the point of view of the remediation of the groundwater environment of the cities, but also from the point of view of water resources economics of enhancing water supply in the Kingdom.
With this in mind, a case study is presented for the city of Riyadh, where the quantity and quality of polluted drainage was measured. Five gaging and sampling stations established at the outfalls of the cities' drainage network and the quality and quantity of the drainage were monitored over a period of six years. The quality and quantity of drainage is such that it is well within treatment schemes and may well be used to recharge aquifers in the region.

Key words: Groundwater remediation, recharge, urban drainage, water table rise, wastewater treatment.

1. INTRODUCTION

In the past 20 years or so, the city of Riyadh, in the Kingdom of Saudi Arabia, has undergone massive urbanization that has resulted in the vast growth of its population, which has, in turn, resulted in the importation of large quantities of expensive water into the city's environment. Presently, the city has an approximate population of 3.25 million, and requires about 2,000,000 m^3 of water per day, nearly two-thirds of which is pumped from desalination plants in the industrial city of Jubail situated 500 km away. As a result of this urbanization, two significant hydrological changes have taken place in the city. These are: (1) an increase in surface runoff as a result of the increase in imperviousness; and (2) a rise in the water table. The increase in surface runoff has been studied by Ishaq and Khararjian (1988), whereas the problem of water table rise in Riyadh has been investigated by several authors (Bureau de Recharches Geologique et Minieres, 1978; Sendil et al., 1983; Shammas, 1984; "Groundwater," 1985; Langsdorf, 1987). These authors suggest that the rise in water table could be due to a number of contributing factors such as: (1) infiltration of irrigated water; (2) leakage from water supply/foul sewage lines; (3) overflow from septic tanks; (4) natural recharge; and (5) movement of ground water from adjoining areas.

Both the surface runoff and the subsurface drainage are collected by the city's storm drainage network and are discharged through three main outlets into Wadi Hanifa that runs along the southwestern periphery of the city. Thus, finding ways and means of reusing this water becomes an attractive proposition, not only from the point of view of water-conservation economics, but also from the standpoint of taking remedial measures for solving the problem of the rise in the water table. Hence, the quality and quantity of this drainage must be determined before treatment levels can be recommended for appropriate use.

In the past, several authors (Ishaq, 1986; Ishaq and Khararjian, 1988; DeGuida and Clarkson, 1987; Frasier, 1980; Fink et al., 1979; School and Aldon, 1978) have investigated the many aspects related to the possibility of utilizing storm runoff and subsurface drainage from urban cities for irrigation, industrial, and recreational purposes. In particular, the work of Field and Fan (1981) has direct implications to the study reported here. They presented treatment levels required of urban storm runoff for use in industry, irrigation, and recreation. However, there is only one case (Wright and Toit, 1996) in South Africa where the urban drainage has been utilized to recharge aquifers. In the case of Riyadh and its surroundings, the geomorphology is almost ideally suited for the recharge of the urban drainage.

2. RIYADH STORM DRAINAGE SYSTEM

Most of the city of Riyadh is situated within the natural watersheds of the three main wadis, namely, Hanifa and its two tributaries, Al-Laisan and Al-Batha. The urbanized area of the city generally lies in the Al-Batha watershed. Some areas in the west, including Al-Nasiriyah and Ulayah fall within the Al-Laisan watershed. Al-Badiah and areas surrounding West Ship Street drain directly to Wadi Hanifa. The fringe areas to the east and south naturally drain away from the city area. Runoff from the northern part of this region soaks away into the desert in the east. Runoff from the southern part eventually outfalls into Wadi Hanifa, south of Riyadh (Figure 1).

The total area of the city can be divided into five major drainage areas. These are the Al-Batha area, the north area, the Al-Laisan area, the Hanifa area, and the east area, as shown in Figure 1. These areas, in general, coincide with the natural Wadi boundaries. The one exception, however, is an artificial division of the Al-Batha watershed into a northern and southern portion by a drainage boundary running roughly between Al-Nasiriyah and the old airport. The natural drainage of this large area has been diverted westward to Wadi Al-Laisan. This reduction of the natural Al-Batha watershed, by about one-third, effectively isolates the upper Al-Batha basin from the lower portion. This has been done to limit the size of the Al-Batha drainage area, thus reducing the amount of runoff passing through the core of the city center where so many flooding problems have been experienced.

The main drainage channel for the Al-Batha area generally follows the course of the wadi from an upper limit, south of the old airport to its confluence with the Wadi Hanifa south of the city, just past the Manfuha sanitary treatment plant. The outfall here became the natural choice for a gaging and sampling station. This drainage network, along with the location of the gaging station, is shown in Figure 1.

This network primarily consists of single and double box culverts, except for the last 500-m section, which is a trapezoidal open channel, 16-m wide. The box culverts range in size from 2 m × 2 m to 4 m × 8 m. The drainage area of this network is approximately 1,450 ha and consists of 9 subcatchments. Storm drainage is primarily from streets and parking lots that have slopes ranging from 1 to 4%. There is, however, a very large quantity of ground water (base flow) being discharged by this drainage system. The discharge is a direct result of the rising water table in the area and takes place through weep holes connected to the media through a patch of gravel.

In addition to the outfall at Manfuha, a convenient location for monitoring the changes in quality and quantity in this network would be at the confluence of the drainage network in the northern half of the drainage area as shown in Figure 1. This station is termed SW9, whereas that at the outfall is termed SW5. Approximately 300 ha of the northeastern part of the city is drained through station SW9.

The drainage of the northern area, originally the northern part of the Al-Batha watershed, is diverted westward to Wadi Al-Laisan. Effectively, it has become a major tributary of the Al-Laisan watershed and has been treated as a separate drainage area. The main drainage structure for this area is the North Diversion Channel. This channel follows a southwesterly route from the old airport to Wadi Al-Laisan at Al-Nasiriyah, and eventually falls into Wadi Hanifa. The length of this system is approximately 15 km and comprises single and twin box culverts, open channels, and a tunnel 1 km long and 25 m^2 in area. The open channel is the trapezoidal type with a width of 16 m. This system drains an approximate area of 900 ha. Here too, the storm drainage is primarily from streets and parking lots. The outfall here becomes an obvious choice for a gaging and sampling station. This location is also given in Figure 1 and is termed SW1. The only other drainage outfall from the city to Wadi Hanifa is the Westship Channel. This network, under natural conditions, drains the Al-Shimaisi area. However, of late, this drainage line has had the additional task of draining the output from several pumping stations at the Makkah Road construction sites. This station at the outfall is termed SW3. At each of the stations, the facilities consist of a water-level recorder (Stevens Type F) and a Manning's discrete sampler (Model 4501). At stations SW1 and SW5, the gaging and sampling stations were installed on the side of the open channel, whereas at stations SW3 and SW9, the facilities were installed on top of the box culvert.

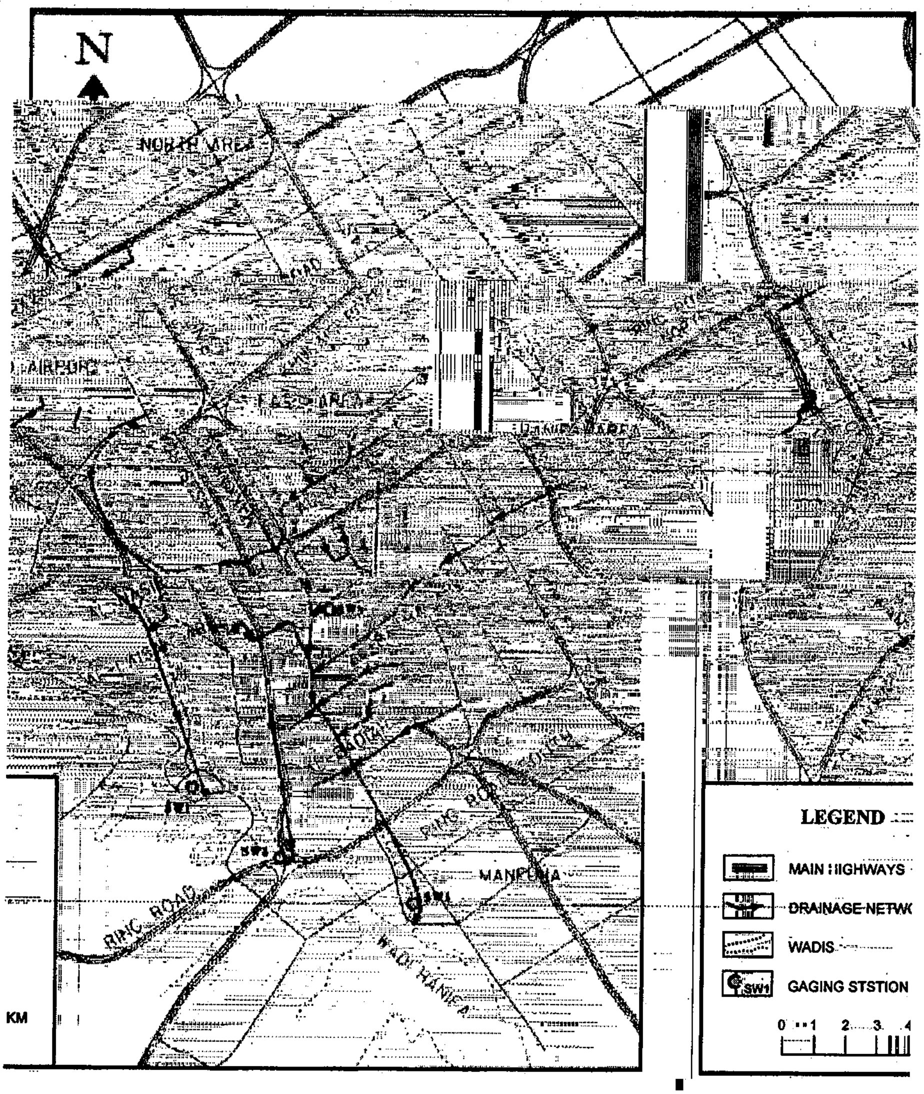

Figure 1. Location map showing gauging and sampling stations in drainage network in Riyadh

3. RUNOFF QUANTITY

The total quantity of water flowing in the stormwater drainage system is made up of: surface runoff and subsurface drainage. Surface runoff is the portion of excess precipitation that finds its way into the drainage system and originates mainly from streets, pavements, parking lots, and rooftops. The subsurface water is the portion that enters the drainage system through weep holes. This component is primarily due to the rise in water table, the causes of which were mentioned earlier. Standard separation techniques have been employed to separate these two components in the hydrographs recorded.

3.1 Surface runoff

The monitoring program was carried out over a period of six years (1984–1989). During the period of study, there were 25 significant storms recorded in all four stations. A summary of the runoff results are given in Table 1.

Table 1. Summary of runoff results of stations SW1, SW3, and SW5

Storm number	Date of Storm	Total rainfall (mm)	Station SW1		Station SW3		Station SW5	
			Total runoff volume (m^3)	Av. runoff coeffi-cient	Total runoff volume (m^3)	Av. runoff coeffi-cient	Total runoff volume (m^3)	Av. runoff coeffi-cient
1	Oct. 15, 1984	10.8	7,030	7.1	15,347	20.3	83,704	28.3
2	Jan. 24, 1985	11.2	10,230	7.7	7,997	10.2	38,626	5.2
3	Dec. 19, 1985	16.4	77,010	35.6	6,119	5.4	40,432	3.4
4	Dec. 21, 1985	27.6	70,530	23.4	10,046	5.2	45,994	3.5
5	Jan. 29, 1986	8.6	32,690	29.4	20,104	35.9	95,723	56.9
6	Mar. 5, 1986	16.0	42,118	20.9	45,024	40.2	173,206	42.7
7	Apr. 4, 1986	17.2	17,342	7.3	60,561	50.3	338,286	68.2
8	Apr. 9, 1986	5.6	42,407	58.4	23,559	60.1	90,145	62.1
9	Apr. 19, 1986	26.1	113,783	35.2	46,589	25.5	150,000	23.5
10	Apr. 24, 1986	24.0	62,586	18.3	46,200	27.5	151,000	23.5
11	Mar. 3, 1987	10.2	32,560	22.0	17,567	24.6	85,927	18.9
12	Mar. 23, 1987	12.2	63,570	46.6	14,232	16.7	42,726	24.2
13	Mar. 25, 1987	22.2	95,727	41.7	63,750	41.0	98,347	12.5
14	Mar. 28, 1987	6.5	33,748	36.6	7,985	17.5	38,472	40.8
15	Jan. 8, 1988	8.4	32,567	26.8	14,748	25.1	47,286	38.8
16	Feb. 2, 1988	26.0	132,756	51.4	40,737	22.4	259,416	53.4
17	Apr. 14, 1988	17.4	28,347	10.2	25,923	21.3	159,461	40.2
18	Apr. 22, 1988	17.4	28,347	59.3	15,767	21.1	82,517	15.8
19	Dec. 26, 1988	8.2	32,437	27.2	17,785	31.0	72,560	12.3
20	Mar. 17, 1989	6.8	19,490	11.7	11,234	23.6	28,275	28.7
21	Mar. 20, 1989	12.6	28,567	14.3	27,222	30.9	92,625	19.0
22	Mar. 24, 1989	5.0	15,675	7.4	7,879	22.5	37,560	51.8
23	Mar. 28, 1989	11.0	63,572	51.7	21,462	27.9	27,767	17.4
24	Apr. 4, 1989	7.0	53,569	65.4	6,578	13.4	27,605	24.2
25	Apr. 12, 1989	22.0	155,195	67.3	48,956	31.8	252,526	61.0

From the results, some of the effects of watershed parameters, especially antecedent moisture conditions (AMC), are quite evident. This effect is shown in the hydrographs for the storms of January 29, 1986, March 5, 1986, and April 9, 1986 where relatively high runoff coefficients have been recorded at all three stations. In all these cases, records indicate that precipitation of very low intensity (trace) were taking place in the previous two or three days. This precipitation, although not enough to produce any significant runoff, was able to bring the moisture content to a relatively high level in the watersheds. The average runoff coefficients for the SW1, SW3, and SW5 watersheds have been 31.3%, 26.0%, and 31.0%, respectively.

3.2 Subsurface water

The subsurface water flowing in the system can be further divided into two components: the dry-weather flow and the discharges from pumped dewatering schemes.

The dry-weather flow is the part of ground water that enters the system through weep holes as a direct result of the rise in the water table, whereas the dewatering component is the amount of water pumped from wells specially constructed at selected sites for the purposes of lowering the water table around specific buildings and construction sites. Table 2 shows the monthly average flows in m^3 at each of the stations SW1, SW3, and SW5, where the average annual flows have been 13.3×10^6 ms^3/yr, 10.2×10^6 m^3/yr, and 29.9×10^6 m^3/yr, respectively. Large flows recorded in station SW5 in the months of April, May, June, and July are primarily due to excessive pumping in dewatering schemes. Though the highest number of dewatering schemes are in fact found in the watershed SW5, the pumpage has been quite random at all three watersheds.

A very important pattern was observed in the plot of the normalized subsurface flows in the three stations for each month when compared with the normalized average precipitation for each month, that is, in the rainless summer months of June, July, August, September, and October, rather large subsurface discharges are observed. This can only be attributed to the most intense irrigation activity that takes place during these months.

Table 2. Mean monthly dry-weather flow at stations SW1, SW3, SW5

Month	Station SW1 flow (m^3/month)	Station SW3 flow (m^3/month)	Station SW5 flow (m^3/month)
January	38,960	29,840	72,620
February	32,650	26,480	64,040
March	30,030	36,970	88,460
April	32,990	15,060	125,950
May	31,630	20,480	98,960
June	28,940	24,640	111,440
July	37,150	29,320	109,110
August	40,100	30,430	91,750
September	41,060	28,150	76,230
October	43,770	29,170	27,640
November	41,460	31,480	34,610
December	40,150	33,310	83,590

4. RUNOFF QUALITY

Details of the four sampling stations (SW1, SW3, SW5, SW9) are already provided in the quantity section. Station SW9 was only installed to determine the quality and quantity variations in the upper and lower halves of the SW5 watershed. The quality of storm runoff must be distinguished from that of the dry-weather flow.

4.1 Subsurface water quality

All four drainage systems SW1, SW3, SW5, and SW9 have recorded substantial continuous dry-weather flow that is fairly polluted with characteristics similar to those of secondary treated domestic wastewater. Tables 3 and 4 show the composite values of various quality parameters and heavy metals of the dry-weather flow characteristics for stations SW1, SW3, and SW5.

Table 3. Summary of composite quality characteristics of dry-weather flow samples
collected at SW1, SW3, and SW5 sampling stations in Riyadh

Station	SS (mg/L)	TDS (mg/L)	Alka-linity (mg/L)	Total hard-ness (mg/L)	COD (mg/L)	TKN (mg/L)	NO_2 + NO_3 (mg/L)	T.Ph. (mg/L)	Cl (mg/L)	SO_4 (mg/L)
SW1	42	2,367	72	988	122	3.42	4.01	0.22	335	1,252
SW2	61	1,987	97	724	104	4.23	4.32	0.36	330	1,152
SW3	81	2,041	148	864	116	5.08	4.86	0.56	292	1,022

SS : Suspended solids; TKN : Total Kjeldhal nitrogen
TDS : Total dissolved solids; T.Ph. : Total phosphate
COD : Chemical oxygen demand

Table 4. Summary of heavy metals analysis of dry-weather flow samples collected at SW1, SW3, and SW5 sampling stations in Riyadh

Station	Cu (mg/L)	Cr (mg/L)	Ni (mg/L)	Pb (mg/L)	Cd (mg/L)	Fe (mg/L)	Zn (mg/L)	Na (mg/L)	K (mg/L)
SW1	0.09	0.20	0.02	0.04	0.15	5.18	0.40	208	11.8
SW3	0.10	0.19	0.01	0.03	0.05	4.19	0.45	198	10.2
SW5	0.19	0.20	0.025	0.02	0.025	4.98	0.32	228	13.7

In the case of most of the parameters, the dilution effect was clearly evident after a rainstorm, except for the parameters suspended solids, COD, and TKN. These parameters increased during and after many rainstorms. In general, the following observations were made at each of the four stations:

- Station SW1: Like station SW5, the dry-weather flow here showed a high concentration of total solids. Hardness remained at the very hard level. Organic matters in the samples remained low. Although sulphates exceeded chlorides, nutrients were deficient in the samples at this station.
- Station SW3: Significant flow takes place at this station only when dewatering schemes discharge their water into this drainage network. In comparison with other stations, SW3 showed low mineral concentrations represented by conductivity and TDS. This water may be classified as moderately hard and had very low organic content estimated as COD. Nutrients like NO_3 and phosphorus, remained low. Though heavy metals in general were rather low, iron concentrations were at significant levels.

- Station SW5: The physicochemical characteristics of the samples analyzed over the period of study showed little fluctuation. Suspended solids remained around the 500 mg/l level. Total and dissolved solids continued to be a mirror image of each other and showed a high concentration that could be attributed to the prevalent very hard state of the water. Sulphate contents of samples analyzed far exceeded that of chlorides. These samples were characterized by low concentration of organic matter, as indicated by low COD values. The samples from this station were not enriched with nutrients like various species of nitrogen and phosphorus.
- Station SW9: Subject to dilution effects, the flow from this station is included in the flow at station SW5. Samples analyzed from this station showed high mineral concentration represented by conductivity and TDS. Hardness remained at the very hard level. Nutrient concentration, represented by various species of nitrogen and phosphorus, remained low, and with the concentration of organic matter, here too, the sulphate level far exceeded that of chlorides.

The diurnal variation of selected quality parameters (total hardness and TDS) is shown in Figure 2. From this plot, it can be seen that there are no diurnal changes in the quality of dry-weather flow in all four stations, and that the quality parameters vary within a narrow range, the poorest quality being at SW1 followed by SW5 and SW9. The flow at SW3 is a result of discharges from pumped dewatering schemes, hence, its quality is significantly different (of better quality) than those at the other three stations.

When the quality parameters over the years were compared, there appeared to be no significant changes in the quality of dry-weather flow over the past six years. One may further infer from this that the source of ground water over the last six years has remained unchanged.

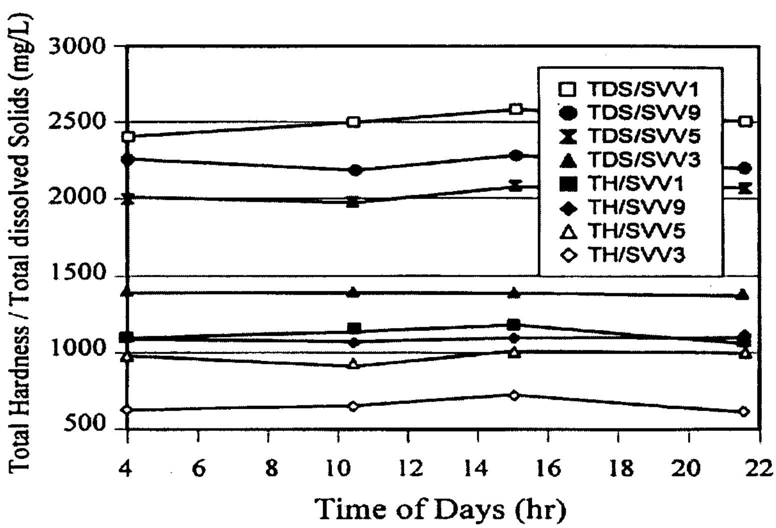

Figure 2. Diurnal variation of total hardness and TDS for subsurface flow at stations SW1, SW3 and SW5

5. TREATMENT ALTERNATIVES AND RECHARGE

The reuse potential of the storm runoff in Riyadh is rather high. With continuous dry-weather flow, whose characteristics are similar to that of secondary treated wastewaters, a year-round

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Groundwater Recharge and Development in the Shallow Coastal Aquifer with Special Reference to the Groundwater Quality

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GROUNDWATER RECHARGE AND DEVELOPMENT IN THE SHALLOW COASTAL AQUIFER WITH SPECIAL REFERENCE TO THE GROUNDWATER QUALITY

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Abstract

In the coastal aquifers of Kerala, the southwestern province of India, the complex geological sets up and the inadequate recharge cause a general degradation in water quality. The study area, which lies along the coastal plain of the central Kerala has widespread decline in the groundwater level in recent years due to the combined effects of rise in population, uncontrolled sand mining from the river beds and deforestation in the Western Ghats. The effects of groundwater pollution and seawater incursion are being reported increasingly. Due to the high demand of groundwater to cater to the needs of the thick population in the coastal zone, a variety of responses are being forged to mitigate or even reverse these. One such response gaining popularity in the state is groundwater recharge. The traditional rainwater harvesting, which has been experimented for groundwater recharge in the coastal area of Ernakulam District proved to be promising and successful. The induced variation due to groundwater recharge was observed in the southern part of the study area as inferred from the geo-chemical studies and long-term trend analysis of groundwater level. The purpose of the paper is to document the impact due to groundwater recharge through rainwater harvesting on groundwater quality and to evaluate the suitability of such techniques elsewhere in similar areas.

Key words: Kerala, geo-chemical studies, hydrograph, rainwater harvesting

Introduction

In spite of heavy rainfall (3100mm/yr) and large number of rivers (44 nos), number of places in the hill tracts and other elevated areas along the midlands of Kerala experience severe drought during the summer months (Paul and George Abe, 1998). This is due to the peculiarity of the terrain characteristics, which promotes high runoff and is therefore hydro-geologically unfavorable for normal groundwater recharge. The recurring incidents of drying up of river beds and streams resulted the non availability of water resource for groundwater recharge in the costal areas during the summer months (February to May) which creates many environmental problems in the coastal zone such as saline intrusion, improper flushing of tidal streams and general ecological degradation. These problems are compounding year after year and are often triggered by activities like uncontrolled sand mining in the riverbeds, deforestation in the Western Ghats etc.

Many studies show that situation in the shallow aquifer in the coastal zone connected to the quality of groundwater is alarming amidst plenty of water all around. Owing to the high demand of groundwater for catering to the needs of thick population in the coastal zone, mitigation of the deterioration in the quality of groundwater in a shallow coastal aquifer is initiated through groundwater recharge. The top priority was given for the traditional water harvesting system in Chellanam Panchayath of Ernakulam District, which was carried out in combination with simple modern technology. The first hand information itself was promising and proved to be a viable.method in meeting the water requirements and also recharging the shallow aquifer. The paper presents detailed response to the development of groundwater recharge to restore supplies from a depleted coastal aquifer.

Study area and its environs

The study area of 60 km^2, extending from south 'Chellanam' to Fort Cochin, Ernakulam District, Kerala (Fig. 1) lies between latitudes 9^{0}47'N and 9^{0}58'N and longitudes 76^{0}13'E and 76^{0}21'E. Bounded by sea on the west, it is crisscrossed by many backwater channels on the other three sides (Soman, 1997). Geologically, the area comprises of fine to medium sand in the north and northwestern sides. However, the gradation of the shallow sediments gets finer towards the southern side (Rajendran et al., 2002). During rainy seasons, the sea becomes rough and encroaches towards land and during summer seasons the saline water finds its way through the inlets from the northern side. The quality of water in the shallow and deeper zones is brackish. Water table fluctuates from 0.25 m to 1.2 m. Diurnal and seasonal water level variations along with evaporation permit the admixing of saline water in the shallow aquifer. The groundwater here is further vulnerable because of stagnation of water holds within the tidal channel due to the artificial barrier built across the southern side of Vembanad Lake at Tannermukkam

Need for groundwater recharge

The coastal sedimentary formation serves as excellent aquifer and the average groundwater potential of this region is estimated to be more than 0.3MCM/Km (CGWB, 1992). In the shallow coastal aquifer open wells are the dominant groundwater abstraction structures and the density of the open wells in the coastal area is high in the range of 400 wells/km^2. The population of Kerala was 655/km^2 in 1981. This had grown up to 749/km^2 in 1991, which accounts highest in the country. The population in the coastal zone is usually high and according to the census of 1991 the population in the study area is estimated to be 1717/km^2

(Land use board, 1995). Need for groundwater is increasing in tune with the population and urbanization in the recent years. In the study area with the absence of efficient protected water supply, the drinking water scarcity in the area was enormously high and people equally suffer for their non-domestic need also. This forced the people to try the rainwater harvesting.

Rainfall pattern of the study area

Kerala enjoys a tropical monsoon climate and receives a very heavy rainfall of about 3100 mm, of which 69% is received during the Southwest monsoon (June to September), 16% during Northeast monsoon (October to December) and the rest as summer showers. Based on the annual rainfall data at Odakkali, Ernakulam District (near to the study area), the estimated evaporation loss is 822.6 mm and soil moisture requirement is 150 mm, with a net water surplus of 2100 mm for use/conservation. The rainwater collected over a rooftop of 100 m^2 area is estimated to be 300,000 litres (Bhowmick. et al., 2000). A comparison of average rainfall of Kerala and Ernakulam District is given in Table.1, which shows that the study area has rainfall in all the twelve months suggesting good scope for rainwater harvesting. Depleted coastal aquifers in the Moti Raya Village of Gujarath, Western India had been successfully regenerated through rainwater harvesting by improving the quality and quantity of groundwater even though the average annual rainfall was only about 380mm (Raju, 1999).

Groundwater recharging technique

Wide range of successful traditional water harvesting techniques had been practiced by the ancient people long ago, which are not only simple but also cost effective and efficient. These traditional methods had been the backbone of many ancient agricultural and domestic activities in the past were declined sharply by the advent of modernization. As in the past, the rainwater harvesting has got a good capability to play on with the need of the hour as conservation and preservation of water resources is an urgent requirement to be done. In the study area two methods of harvesting techniques were adopted in the recent past as part of people's campaign project to alleviate acute water scarcity. One of them is groundwater recharge through rainwater harvesting (Fig. 2) and the other one is the collection and storage of rainwater in surface Ferro-cement tanks (Fig. 3). The former method is briefly discussed below:

For recharging, pits of 2 x 2 x 2 cubic m dimension, situated 2 m above the summer water table level in the area were used. These pits were filled with clear river sand leaving half-meter depth from the ground, which was filled with local clay. The harvested rainwater from the rooftop was then channeled into the recharging pit. A hand pump can draw water from this for domestic purpose. The water stored in the pit above the general water table creates a small pressure head, which moves from the radiating center to its sides along the direction of the groundwater flow flushing the existing aquifer system through and within the porous formation. The number of pipes, area and the depth of the pit can be increased for higher storage depending upon the requirement. Further it helps to have a storage reservoir for small groups or communities.

Materials and methods

A total number of 28 water samples were collected from open wells of the study area from two similar seasons (post monsoon) viz. 1999 and 2000 respectively. A preliminary investigation has been carried out in the year 1999 by collecting twelve water samples from the open wells when the rainwater-harvesting project was only begun. A detailed case study analysis was carried in the southern half of the study area in the later year. During this period five water samples were collected from open wells and kept as index wells to understand the general groundwater quality of the area during the sampling period. They were particularly selected from the location beyond the influence of the recharging wells and were at least

separated 500m apart from the nearest recharging well. Four samples were collected from the recharging wells and seven from the adjacent open wells, which are situated 50 to 100m away from the recharging wells. Water samples from the recharging wells and the adjacent wells were studied together as five coupled units and studied in terms of spatial distance and direction of regional groundwater flow.
Sampling was carried out during this period as the rate of flow from the surface water to groundwater reaches maximum and the effect on the neighboring wells will be high. Collections of water samples during both periods were completed in a single day and the locations of sampling wells are shown in Fig. 1.

Samples were analyzed for determining the parameters viz. Electrical conductivity (EC), Hydrogen-ion concentration (pH), Total dissolved solids (TDS) and Cl and discussed to understand the role of groundwater recharge in the study area (Table 2).

Long term trend analysis was carried out by comparing hydrographs prepared from the available data (Fig.4) obtained from three selected observation wells of state groundwater department to understand the role of groundwater recharge through rainwater harvesting.

Results and discussions

Electrical conductivity (EC)

Chemically pure water has low conductance but in the presence of dissociated ions it becomes conductive. The EC values of the samples during the period of 1999 were in the range of 8.7 to 222 mmhos.cm^{-1}. Majority of the wells had higher values and were above 30 mmhos.cm^{-1} and could therefore be concluded as highly mineralized. EC in the index wells during the period of 2000 were also high, ranging from 54.5 to 113.5 mmhos.cm^{-1} and was found to have a close resemblance with the values obtained during the previous year. However in the recharge wells, the values were low and ranged from 7.2 to 24 mmhos.cm^{-1}. In the adjacent open wells, it was slightly higher but comparatively lower than the index wells. Close observations of coupled units I and IV indicate that the EC values in the adjacent wells were comparatively much higher (increased from 15.1 to 22.3 mmhos.cm^{-1} and 8 to 12.6 mmhos.cm^{-1} respectively) than the values of the recharge well. In unit V, even though, the adjacent well was separated only by 25 m it showed a high value. In unit II, the EC of the well in the northern side was much higher than the one in the southern side. Considering the distance and direction, the adjacent open wells are only 25 m away from recharge wells in the NNW and NNE directions respectively for units I & V; but they show high EC values indicating less recharge. Whereas, in unit IV the distance is 80 m but the values were much lower as compared to the adjacent wells in other directions. This clearly indicates that the groundwater recharge was prominent in the adjacent wells and the influence was prominent in the south and southeastern sides.

Hydrogen-ion concentration (pH)

The presence of hydrogen concentration is indicated by pH. It is the measure of acidity and alkalinity. According to the Indian standard the desired limit of pH is in the range of 6.5 - 8.5. The analysis of the water samples collected during the year 1999 shows that most of the samples were above the desired limit and were alkaline. This alkalinity might be due to the presence of dissociated anions. The general character of the water samples from the southern and northern sides during this period suggests the presence of secondary salinity in the groundwater. This may be induced due to the mixing of seawater and brackish water, which takes place within the shallow aquifer as it lies in the zone of transition. However, in the southern half during 2000, the values were within the admissible limits except for two index wells. The high pH values indicate the presence of dominant salinity in the shallow aquifer system. This indicates the presence of fine aquifer sediments mixed with clay and mud, which are unable to flush off the salts during the monsoon rain and hence retained longer. There is no much distinct variation seen among the different wells selected for the case study, indicating the influence of groundwater recharge, which resulted in total saturation through percolation and movement of pure rain water through the porous formations underground.

Total dissolved solids (TDS)

TDS values in most of the wells during 1999 are above the permissible limit according to the Indian standard (1500 ppm). The general water quality of the wells as inferred from the high values of TDS may be due to concentration of salts indicating salinity present in the area even after the monsoon rains. All the water samples in the index wells, 2000 show higher values except well No. 16. Also, they had a close resemblance with values of the samples collected during the previous year. Hence it may be concluded that the hydro-geochemical characters during both the seasons were more or less identical. In recharge wells of the case study, coupled units I, II, IV, and V had low TDS values. In the adjacent open wells the values were progressively increasing with respect to the spatial distance. The high TDS value in the recharge wells of unit III might be due to the presence of fine aquifer sediments, which retain the salts longer than other sediments. A comparative increase was found in the TDS value of adjacent wells in coupled unit II. Amongst them the adjacent well located in the northern side had less influence than the one in the southern side. The values of the above northern side adjacent well were almost double that of the recharge well. The values of TDS during the period of 1999 had a close resemblance with the values of the index wells, 2000. But anomalous variation could be seen in the recharge and adjacent wells suggesting the influence of groundwater recharge in the southern side during 2000.

Chloride (Cl)

Chloride content is generally taken as an index of impurity of water. The values of Cl in the index wells during the period of 1999 show higher values and are above the permissible limit of 250 ppm. In the eastern side of the study area, wells (Nos. 1,6,8 & 10) separated by more than 1 km distance from the sea, had low Cl values. This can be due to the combined effect of the flushing of the tidal channels that causes low values in brackish water and due to the monsoon rains, which dilute considerably the groundwater of the wells. During 2000, the index wells, showed higher values of Cl. With regard to other parameters, the values did not vary much during the two consecutive post monsoon seasons and it was concluded that the hydro-geochemical variations of shallow aquifer groundwater do no change much in the post monsoon seasons irrespective of the years. In recharge wells the Cl content was below the permissible limit (250 ppm). However, there was slightly higher concentration (550 ppm) of Cl in the recharge well No.23 (unit III). This can be due to the proximity of the well to the tidal channel and the poor muddy sediments present in the aquifer system. The clogging nature of sediments permit only intermittent flushing and hence the impurity was sustained longer as compared to other wells. The Cl content in the adjacent wells progressively increases with respect to spatial distance and direction. In all adjacent wells, the Cl content is below the permissible upper limit (1000 ppm) except in the well (unit II), located to the north and separated by an equal distance, has a much higher Cl content. This clearly indicates that the influence of recharge is more towards the southern side indicating the direction of flow of groundwater from north to south. The less influence of the groundwater recharge in the NNE and NNW is also evident from the values of units I and V separated by an equal distance of 25 m. This clearly shows that the anomalous change in the groundwater quality in the different wells is due to the intensity of recharge, which is more in the south and southwestern directions.

Hydrographs

Fluctuation of groundwater level in the shallow flat lying coastal aquifers are usually very less hence short term trend analysis of water level would sometimes be misleading. How ever a long-term trend analysis would be more useful in such situation especially to understand small fluctuations. Hence monitoring the response of water level due to groundwater recharge was carried out by analyzing the data from three monthly observation wells (29, 30 and 31), which are located at Mattancheri, Kumbalangi and Chellanam respectively (Fig. 1). Based on the available data, hydrographs were prepared by using the monthly observation well data during the period from Sep 1977 to April 2002 (Data during the period from Sep 83 - May 87, Sep 92 - Oct 94 and from Feb 98 - Feb 00 was not available). The method of least square for best fitting line was adopted to find out the slope of the trend line. Assuming an equal rainfall distribution in all the said locations, groundwater level fluctuation of the three monthly observation wells was compared. Hydrographs shows their three different types of responses inferred from the analysis (Fig. 4).

The long-term trend analysis of the monthly observation well in the northern extremity shows that the trend is falling with a slope value of - 0.028 mbgl. A close observation of the peak values of this well shows that the shift in the trend was due to the steady fall in the water level over the years. It might be due to the steady increase in demand of groundwater for non domestic needs as well due to the decrease in the groundwater recharge caused by the change in the land use pattern like the construction of asphalt roads, filling up of natural ponds and other water bodies, densely packed dwellings with cementing yards etc due to urbanization. A rising trend could be noted in the well located in the southern extremity with a slope value of + 0.003 mbgls, this rising trend could be due to the anomalous rise in the peak values noted since the pre monsoon period of 2000. Comparing with the peak values of the northern most well the anomalous change in the values in the southern most well could be attributed only due to the development of groundwater through groundwater recharge initiated in the area during the particular period. However there is no change in the trend observed from the peak values in the well for any anomalous change indicating an equilibrium condition in the water level due to under development of groundwater resources in the area. Comparing to the other two areas the density of population in this area is very less and energized lifting devices are also not common. Thus the comparison of the hydrographs of the study area clearly depicts the role of groundwater recharge in the southern side as inferred from the rising trend of water level in the area.

Conclusion

The analysis of the water samples from the study area during the post monsoon period of 1999 indicates that the groundwater present in the shallow aquifer of the region are poor in quality and beyond the potable limit as per the Indian standard. The groundwater from the index wells collected from the southern half of the study area during the period of 2000 bears close resemblance to the samples collected during the previous. In the case study analysis of the wells located in the southern half of the study area shows that influence of groundwater recharge is evident in the adjacent wells separated by a distance less than 50m. The direction of influence is more towards the south and along the flow direction rather than the north and other sides. The long-term trend analysis of groundwater level also clearly indicates the role of groundwater development in the southern half through groundwater recharge as inferred from the hydrographs (Fig.4). Though the slope of the trend line was very small, the change brought out in the water quality was quite appreciable and promising. The implementation of the scheme in every rooftop will undoubtedly improve the water quality in a long run. Therefore it may be concluded that the proposed technique is viable in meeting the water requirement and also recharging the aquifer in similar environments. The study also recommends necessity of groundwater recharge in the northern half to cater the rising demand as inferred from the long trend analysis.

Acknowledgement

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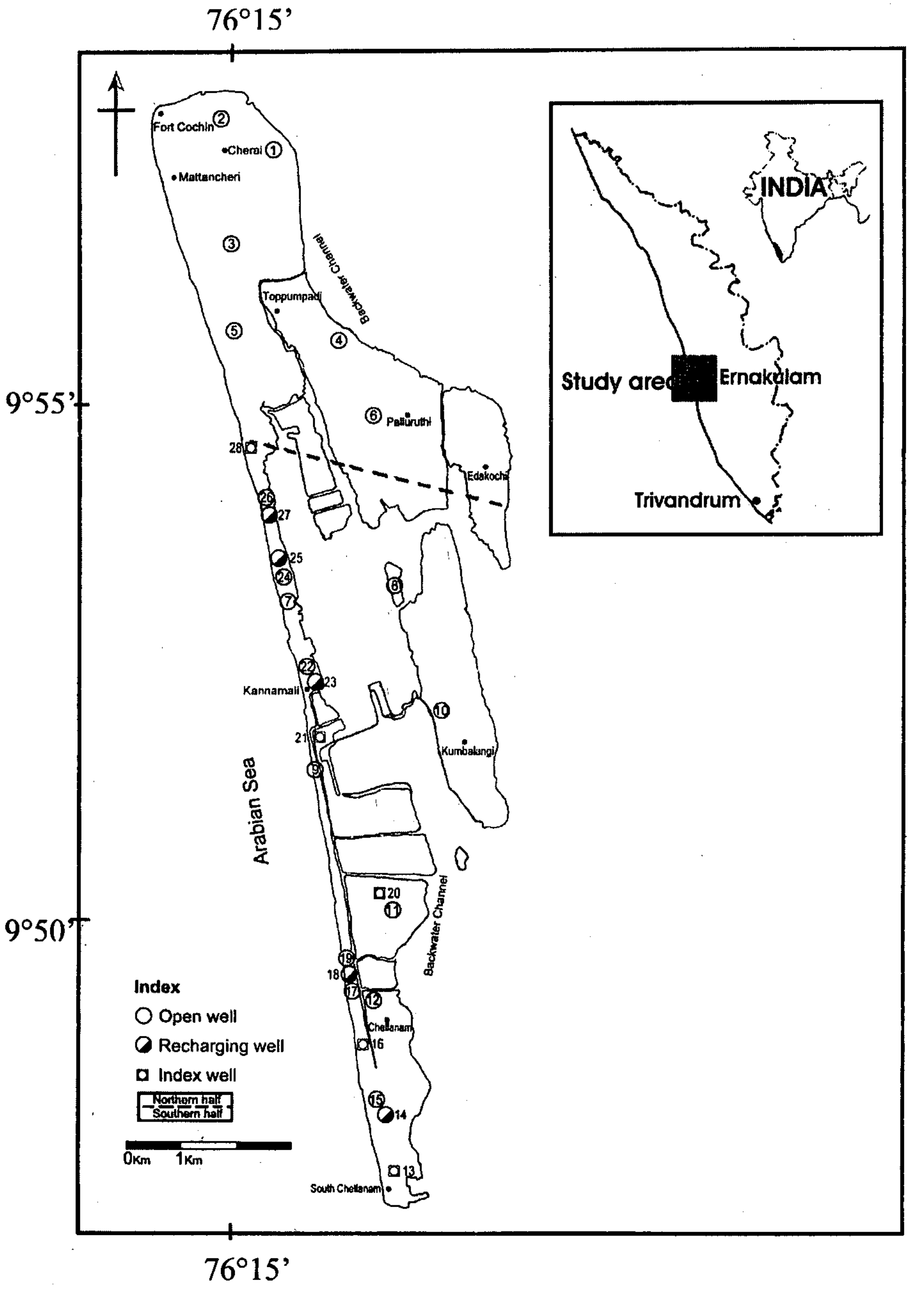


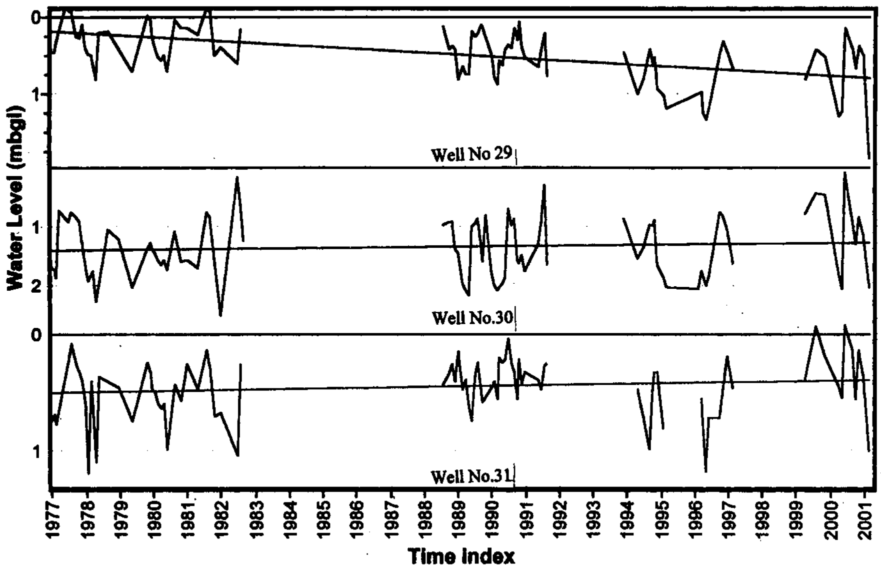
Figure 1 Map showing sample (well) locations

Table 1:Normal rainfall in Kerala state and Eranakulam districts in different months

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Kerala State												
14	17	39	112	256	691	760	433	247	288	163	42	3063
Eranakualm District												
15	17	41	134	318	740	721	451	288	312	172	45	3254

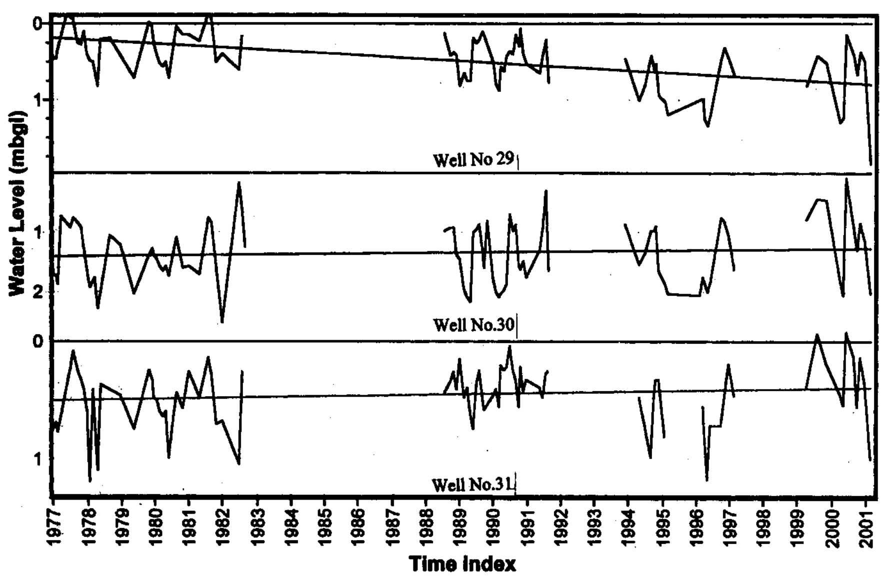
Table 2. Chemical analysis of groundwater during 1999 (Well Nos. 1-12) & 2000 (Well Nos. 13-28)

Well No		Type of Well		pH	EC	TDS	Cl
Chemical analysis 1999, Northern side							
1		Open well		8.9	74.0	820	40
2		Open well		8.8	29.4	2713	360
3		Open well		8.4	21.0	1410	1000
4		Open well		8.6	45.0	1600	300
5		Open well		9.0	8.7	1500	500
6		Open well		9.0	117.0	890	90
Chemical analysis 1999, Southern side							
7		Open well		8.8	48.0	1504	700
8		Open well		8.7	33.0	913	100
9		Open well		9.0	126.0	1500	400
10		Open well		9.0	76.0	1491	200
11		Open well		9.1	10.1	1693	1000
12		Open well		8.9	10.2	1723	700
Chemical analysis 2000, Southern side							
Well No	Coupled Unit	Type of Well	Distance and direction from recharge well	pH	EC	TDS	Cl
13		Index well		8.08	113.5	7720	4002
20		Index well		8.79	54.5	2930	1475
21		Index well		8.23	129.1	2100	1578
28		Index well		8.6	70.0	1520	675
16		Index well		7.92	46.2	2680	1253
14	I	Recharge well		8.3	15.1	790	251
15		Open well	25 m, NNW	7.84	22.3	1190	453
19	II	Open well	50 m, North	8.04	37.6	2100	820
18		Recharge well		8.31	7.2	260	39
17		Open well	50 m, South	8.1	10.3	780	77
23	III	Recharge well		8.0	24.0	1220	550
22		Open well	50 m, NE	8.37	12.9	650	834
25	IV	Recharge well		7.98	8.0	320	106
24		Open well	80 m, SSE	8.13	12.6	610	174
26	V	Open well	25 m, NNE	8.12	15.0	670	607
27		Recharge well		8.04	7.6	360	48



— Well No.29 (Slope=-0.028) — Well No.30 (Slope=0.000) — Well No.31 (Slope=0.003)

Fig.4 Hydrograph of Wells from Oct 77 to Apr 02 showing different trends



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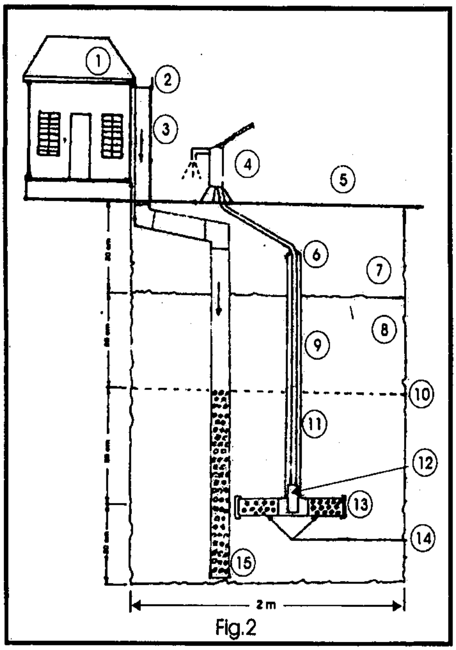

Fig.2

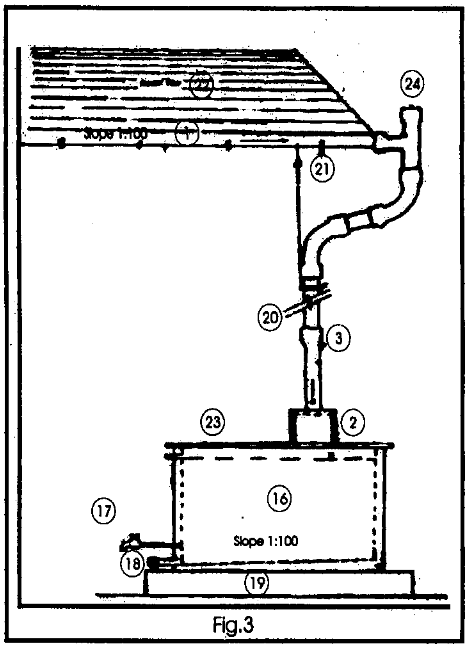

Fig.3

1.Roof top channel
2.Sand Filter
3.P V C pipe
4.Hand pump
5.Earth surface
6.Reducer coupling (2"x1")
7.Top soil
8.River sand
9.Flexible hose(1")
10.Water table level during summer season
11.2"pvc pipe
12.Foot valve
13.End cap
14.Perforated pipe
15.Perforated pipe
16.Ferrocement tank
17.Tap
18.Plug to clean the tank
19.Maisonary platform
20.Clamp
21.Bracket to hold pipe
22.Roof top
23.M H cover opening
24.Loose jointed PVC TEE for diverting water from first few rains away

Fig.2 Cross sectional view of the experimental model for ground water recharge.

Fig.3 Cross sectional view of the arrangement showing rain water storage.

Hydrologic Effects of Climate Change on the Zarqa River Basin-Jordan

Dr. Fayez A. Abdulla (Jordan)

Hydrologic effects of climate change on the Zarqa River basin- Jordan

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Abstract

In this paper, the long-term hydrological responses (runoff and actual evapotranspiration) of a semi-arid catchment to climate changes were analyzed. This catchment is the Zarqa River (Jordan). The climate changes were imposed with twelve hypothetical scenarios. Two of these scenarios were based on the predictions of general circulation models (GCMs) namely Hadley and MPI models. The other ten scenarios are incremental scenarios associated with temperature increased by +2C and +4C and changes in precipitation of 0%, +10%, +20%, -10%, and –20%. These scenarios were used as a basis for observing causal relationships among runoff, air temperature, and precipitation. The Surface-inFiltration-Baseflow (SFB) water balance model that was developed by Boughton (1984) was used for observing these causal relationships. First areal precipitation and potential evapotranspiration of the basin are estimated based on the observed meteorological and hydrological data. The monthly runoff simulations are then investigated through the application of the SFB model. Seven years of meteorological and hydrological data are used for calibrating the model. Another Seven years of the record are used for model validation. The global optimization technique known as shuffled Complex Evolution (SCE) method is used to obtain the optimal parameters of the SFB model. The model performed well for the Zarqa River for which the coefficient of determination was 0.78. The average monthly runoff compared well to the observed runoff. The error of the observed and simulated streamflow is within acceptance limit and found to be around 18 percent. The model performance in the validation stage is reasonable and comparable to those of the calibration stage. Both sets of climate change scenarios resulted in decreases in monthly runoff. Differences in hydrological results among all climate cases due to wide range of changes in climate variables.

Key words: Climate change, Optimization, Rainfall-runoff modeling, Incremental scenarios, Calibration, Validation.

Global patterns of climate change, predicted by General Circulation Models (GCM) forecast a global temperature increase of 1.5o to 4^{o} C with a doubling of the current CO_2 concentration (Houghton et al., 1990; Girogi et al., 1972). Climate change has impacts on water resources, and subsequently, on the sustainability of our environment. Climate changes due to increased atmospheric CO_2 and other trace gasses may affect the water supply for municipal, industrial and agriculture uses (Chang et al., 1992; Lettenmaier and Sheer 1991, Waggoner, 1990).

Lettenmaier et al. (1994) indicated that the most important impacts of global warming would be those associated with changes in runoff and groundwater recharge. They also indicated that in areas with rain-dominated hydrology, it is possible, using simple water balance models to estimate to the sensitivity of runoff to changes in precipitation and evaporation.

In the last 10 years, monthly water balance models have been used to explore the impact of climatic change (Schaake, 1990). For example, Gleick (1987) reviewed various approaches for evaluating the regional hydrologic impacts of global climatic change and presented a series of criteria for choosing among the different methods. He concluded that the use of monthly water balance models appears to offer significant advantages over other methods in accuracy, flexibility, and ease to use. Gleick (1987) also developed and tested a monthly water balance model for climatic impact assessment for the Sacramento basin.

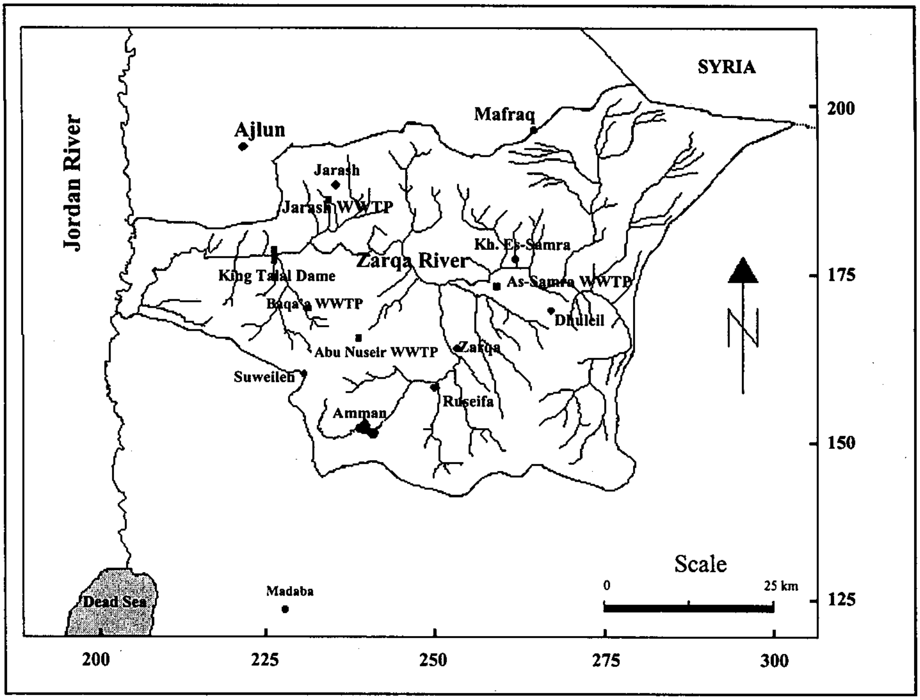
Water balance models have been developed at various time scales, e.g. hourly, daily, monthly, and yearly and to varying degrees of complexity. Francini and Pacciani (1991) presented a detailed review on monthly water balance models. They grouped the monthly models according to their principal objectives and their input data requirements. Conceptual rainfall-runoff models are those based on the water balance equation. Well known examples of this type of models include the Sacramento Model (Burnash et al., 1973), and variable infiltration capacity hydrological model (VIC-2L) (Liang et al., 1994). These models are useful tools in hands of engineers in charge of water resources projects. These models are critical tools for estimating the peak discharge and runoff volume of floods. Usually, the traditional use of monthly water balance models has been to investigate the importance of different hydrologic variables in diverse watersheds. Also monthly water balance models have been used in snowmelt simulation; climate change assessment; flow forecasting and water project design; and flow record generation in ungauged catchments.

In this study, the Zarqa River System, a major surface water system, was selected to reflect actual changes to the existing water resources of Jordan. The monthly runoff for the Zarqa River basin, was assessed through the application of the Surface-infiltration-Base flow (SFB) water balance model. Areal precipitation and evapotranspiration of the basin are estimated based on the observed meteorological and hydrological data. The water balance Surface infiltration Base flow (SFB) model has been selected due to its simplicity, which requires 5 parameters to be found by calibration. Also this model has been applied previously for climate change studies.

The model was calibrated using meteorological and hydrological records extend from 1981-1988 The validation period extend from 1988-1995. The global optimization technique known as Shuffled Complex Evolution method of Duan et. al (1992) is used to estimate the model parameters. The sum of square differences between the observed and simulated runoff is used as an objective function. Then, the generated climate-change scenarios either those of the GCMs or the incremental scenarios are used as input for the SFB model to assess the impact of climate change on the water budget components of the Zarqa River basin.

2. Study Area Description

The Zarqa River System (Figure 1) of 3300 km^2 is located in northeastern part of Jordan. This catchment is situated between altitude - 350 and 1100 m above mean sea level (a.m.s.l). The eastern part of Zarqa River System is high desert plateau. Toward the west, the basin changes to a highland and then becomes progressively steeper until it reaches the Jordan valley. The basin is covered sparsely with shrub type vegetation. A variety of crops are planted along the river.



Legend:

● **City**

Drainage or Wadi

■ **Wastewater Treatment Plant**

King Talal Reservoir

Fig. (1): Zarqa River System

The study area belongs to King Talal Dam watershed. The dam is located about 42 km northwest of Amman and impounds a reservoir of about 86 MCM. The average annual precipitation in the western part of the catchment reaches about 400 mm, while in the eastern part it rarely exceeds 150 mm. The bulk amount of precipitation falls in the winter season (i. e., between October to May). The beneficiaries of Zarqa River system include households, business entities, industries and farmers.

3. SFB Model Description

The model selected in this study is the water balance Surface Infiltration Base Flow model (SFB) (Figure 2) which was developed by Boughton (1984). This model has been used in a number of studies that focus on the assessment of the impact of climate change. Also, it has been used extensively in Australia as a means of estimating monthly stream flow from rainfall and potential evapotranspiration (Bates et al., 1994; Sumner et al., 1997; Ye et al., 1997; and Abdulla and Al-Badraneh, 2000).

The model requires five parameters to be calibrated. These parameters are: the surface storage capacity of the catchment (S), the daily infiltration capacity (F) that control percolation from surface store to groundwater, the base flow parameter (B), which determining the portion of the daily depletion of groundwater that appears as base flow, the Non-Drainage Component (NDC), which represents the fraction of the upper storage that non-drain. and the deep percolation factor (DPF) which determines the fraction of depletion from the lower storage. The other model parameters are considered fixed as recommended by Boughton (1984) : The maximum limiting rate of evaporation (E_{max} = 8.9 mm/day); and a base flow threshold for the lower store (SDR_{max} = 25 mm) which mean there has to be at least 25 mm of water in the lower store before any base flow occurs.

The model operates on a daily time step, with inputs of daily rainfall and daily potential evaporation. The model runs as follows: incident rainfall begins to fill the surface store, which is depleted each day by evaporation, at the potential rate when the non-drainage component is full. When the non-drainage component of the surface store is not full, then an actual rate of evapotranspiration (ET) is the potential evaporation.

Surface runoff (Qs) occurs when the surface store is full and is described as

$$Q_s = P - F \tanh (P/F) \quad \text{......(1)}$$

In which P is the rainfall excess remaining after the surface store is filled. The lower store is depleted by deep percolation (D_p) and baseflow Q_p which are calculated as

$$D_p = (1\text{-}B)\ DPF\ SS \quad \text{......(2)}$$

$$Q_p = B\ DPF\ (SS - SDR_{max}) \quad \text{......(3)}$$

Where SS ≥ 0 is the depth of water in the lower store.

The non-drainage component is depleted each day by evapo-transpiration. When this component is full, then evaporation occurs at the potential rate (E_{pot}). Otherwise, the actual evaporation rate is determined by

$$E_a = \min \{ E_{max}\ s/(NDC \times S);\ E_{pot}) \quad \text{......(4)}$$

where s ≥ 0 is the depth of water in the non-drainage component of the surface store.

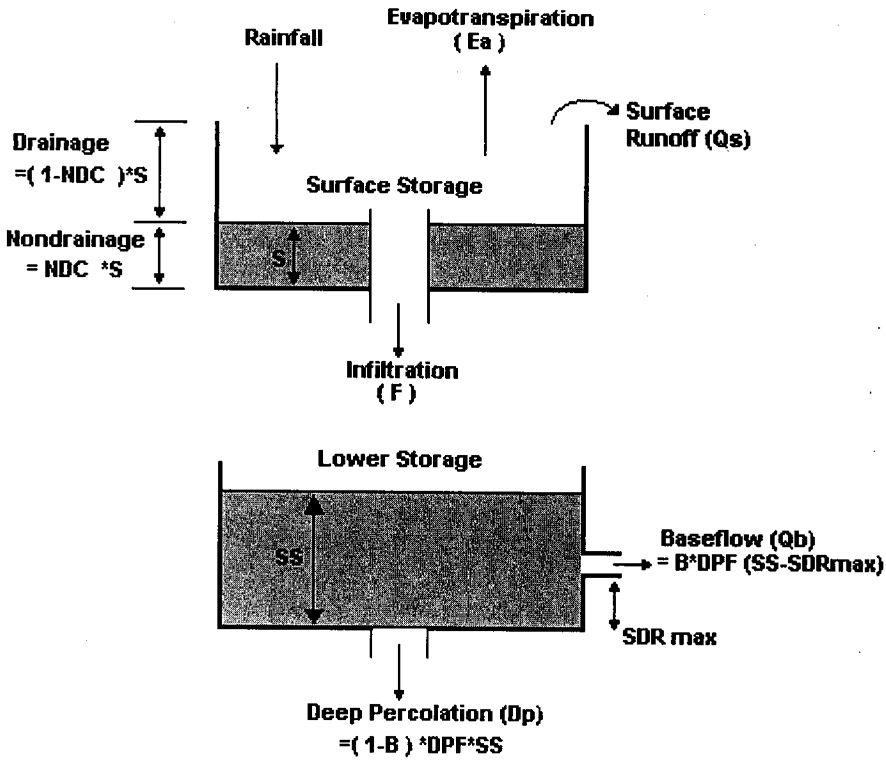


Fig. (2): Schematic representation of the SFB model (after Sumner et al., 1997)

4. Model Application

The Surface- Infiltration- Base Flow (SFB) model is applied to simulate monthly water balance for Zarqa River. The SFB model runs on a daily time step. The most important part of the input data is the rainfall data (mm), and potential evapotranspiration (mm). The output of the model is the estimated runoff (mm) and the evaporation (mm). The model input of areal precipitation for the period 1981 to 1995 of the Zarqa River basin was calculated using the Thiessen method. Six daily rainfall stations were selected for the Zarqa River. Three daily meteorological stations were used in the computation of the area potential evaporation. The monthly streamflow data were obtained from the Ministry of Water and Irrigation. The stream flow data were adjusted by subtracting the effluents of the wastewater treatment plants upstream of the New Jarash Bridge Station.

The SFB model consists of five unknown parameters (*S, F, B, ndc* and *dpf*). These parameters are estimated through model calibration by fitting the outputs of the model to the observed output at the watershed. In this study, a global optimization scheme called the Shuffled Complex Evolution (SCE) method, is employed to obtain the optimum set of the model parameters by minimizing the sum of square differences between the observed and simulated runoff. This method has been recently employed in calibrating several hydrological models by Abdulla et. al (1999), and Summer et al (1997). Two statistical criteria will be used to judge on the degree of success reach by application of the SFB model for the selected catchment. These are percentage error between observed and simulated total runoff and coefficient of determination (R^2).

Calibration Results

The calibration period extend from 1981-1988. During the calibration stage several runs are conducted to check for the most appropriate initial soil storage required by the model. In addition, several independent calibration runs are conducted to select the best seed random generator for the SCE optimization method. It is found that the inappropriate selection of the seed random generator may lead to different local minimum. At least 10 independent runs are performed and the run, which resulted in the minimum objective function, has been selected. The calibration results of the SFB model are reasonably acceptable. In the calibration period from 1981-1988, the relative bias (ΔV%) was less than 18%. However, the R^2 values for the Zarqa River was 0.78. Figure (3) shows the observed and simulated monthly stream-flow for the Zarqa River for the calibration periods. The model performed with different degree of success in terms of matching the observed surface runoff peak flow and time to peak for the tested catchment. The observed and simulated mean monthly runoff for the calibration period is shown in Figure (4a).

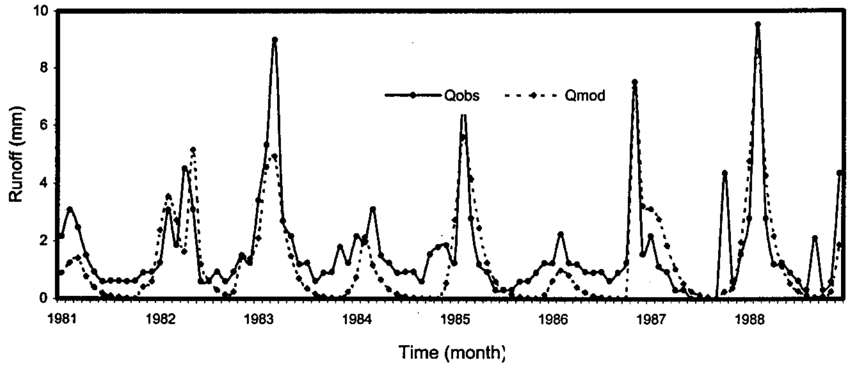


Fig. (3): Observed and simulated monthly runoff for Zarqa River (Calibration period 1981-1988)

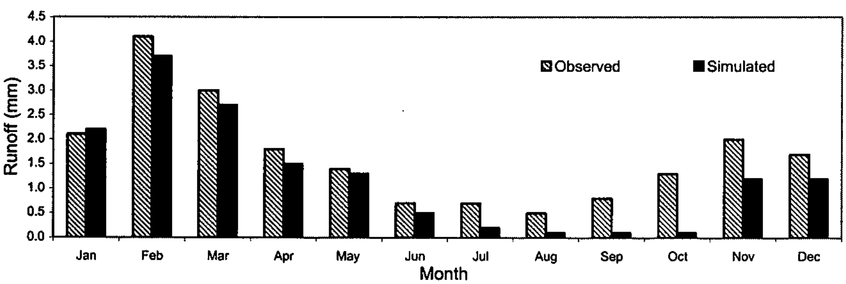


Fig. (4a): Mean Monthly observed and simulated runoff for the calibration period 1981-1987

Validation Results

The optimum parameters obtained in the calibration stage will be used to simulate monthly runoff for the validation period. In this study validation trials is investigated for period 1988-1995. For the validation stage, the correlation coefficient was found to be 0.65. However, the relative bias was approximately 30%. The predicted hydrographic is underestimated but the shape of the hydrographic remains almost the same for Zarqa River. Figure (4b) shows the observed and simulated mean monthly flows for the validation period.

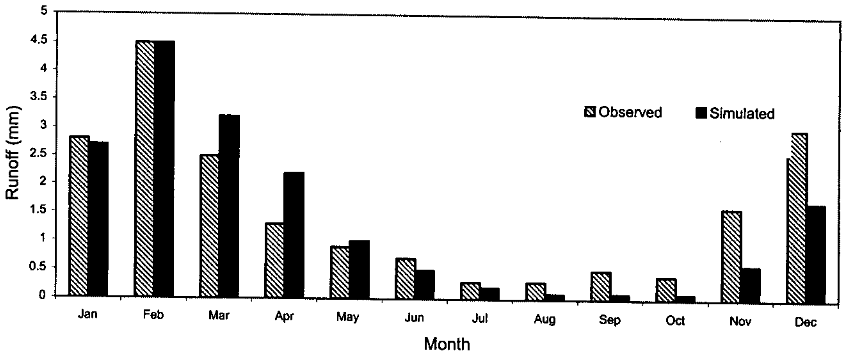


Fig. (4b): Mean monthly observed and simulated runoff for the validation period 1988-1995

Climate Change Scenarios

Forty years (1960-2000) of historical climate data were used to develop a baseline climate scenario (Table 1) for the Zarqa River basin.

Table (1) Baseline climate scenario for Zarqa River basin

	Climatic variable			
Month	Mean Temp(°C)	Min Temp°C	Max Temp°C	Rainfall (mm)
Jan.	7.8	3.3	12.3	62.7
Feb.	8.9	4.0	13.8	54.4
Mar.	11.0	6.0	17.1	49.3
Apr.	16	9.4	22.7	13.6
May	20.5	13.2	27.6	2.7
June	23.8	16.8	30.7	0.07
July	25.2	18.6	31.9	0.0
Aug.	25.4	18.6	32.2	0.0
Sep.	23.6	1606	30.6	0.08
Oct.	20.3	13.6	26.9	8.3
Nov.	14.4	808	20.0	26.7
Dec.	9.5	4.9	14.1	51.3
Annual	17.2	11.1	23.3	273.6

The mean annual temperature is 17.2°C, annual mean minimum temperature is 11.1°C, and annual mean maximum temperature is 23.3°C. Mean annual rainfall is 273.6°Cmm. The monthly variations of these parameters are given in Table (1).

Twelve climate change scenarios representing the possible average climatic conditions around year 2040 were developed. Ten of these scenarios are incremental scenarios suggested as potential scenarios of climate change. These incremental scenarios are associated with two-temperature change of +2°C, and 4°C. Along with each of these temperature changes, changes in precipitation of 0%, +10%, +20%, -10%, -20%. The other two scenarios were based on the outputs of two General Circulation Models (GCMs) namely the Hadley and MPI models.

The output of these models have been retrieved and extracted from IPCC Data Distribution Center for climate change studies. The monthly temperature and precipitation from Hadley and MPI models simulation of current conditions ($1xCO_2$) were compared with observed data (1960-2000) . In Fig (5) the Hadley model output temperature for the current run is in a good agreement with mean monthly temperature for Zarqa River basin, while the MPI tends to over estimate the baseline temperature.

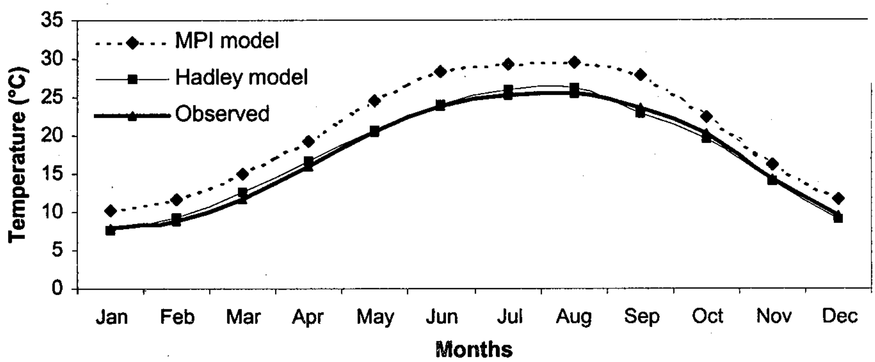


Fig. (5): Comparison of baseline 1960-2000 average mean monthly temperature and 1× CO_2 GCM scenarios for Zarqa River Basin

Temperature and precipitation adjustment statistics for both Hadley and MPI model were used for construction of climate change scenarios for Zarqa River basin., Adjustment statistics for Difference between $2xCO_2$ by 2040 and current $1xCO_2$ scenario by MPI and Hadley models are presented in Table (2) .

Table (2): Statistical adjustment for difference between $2xCO_2$ and current ($1xCO_2$) as estimated Hadley and MPI models for Zarqa River basin.

Month	Hadley Model		MPI Model	
	Temperature Difference	Precipitation Ratio	Temperature Difference	Precipitation Ratio
January	1.43	0.73	1.04	1.07
February	0.98	0.84	0.49	0.64
March	1.29	1.05	0.37	1.28
April	0.71	1.28	1.17	0.91
May	0.31	1.5	1.37	1.77
June	0.95	---	2.29	---
July	0.31	---	2.26	---
August	0.5	---	2.74	---
September	0.8	---	2.51	---
October	1.11	0.87	2.91	1.37
November	0.52	0.79	1.94	0.88
December	1.16	0.7	1.21	0.83
Average	0.85		1.63	

Application of climate change scenarios

The generated incremental and GCMs climate change scenarios were used as a basis for observing causal relationships among runoff, air temperature, and precipitation for Zarqa River basin using the SFB rainfall-runoff model. The goal was to determine how possible changes in the quantity and timing of runoff from changing climate would affect Zarqa River System.

Changes in runoff differ according to the climate scenario and hydrological model applied. Generally, using incremental and GCM scenarios, it was found that serious effects could be expected in basins with currently low total precipitation. Basins with high precipitation appear to be relatively less sensitive. Significant changes could therefore be expected in basin with medium and low runoff.

The effect of increasing air temperatures alone is shown in figure (6). The runoff decreases as temperature increases. The timing of the peak flow is not changed but the magnitudes of these peaks are reduced. The effect of adding or subtracting 20 percent of precipitation alone to the observed record was as expected. Greater precipitation translated into higher runoff volume during winter. The opposite phenomena occurred when precipitation amounts were reduced 20 percent.

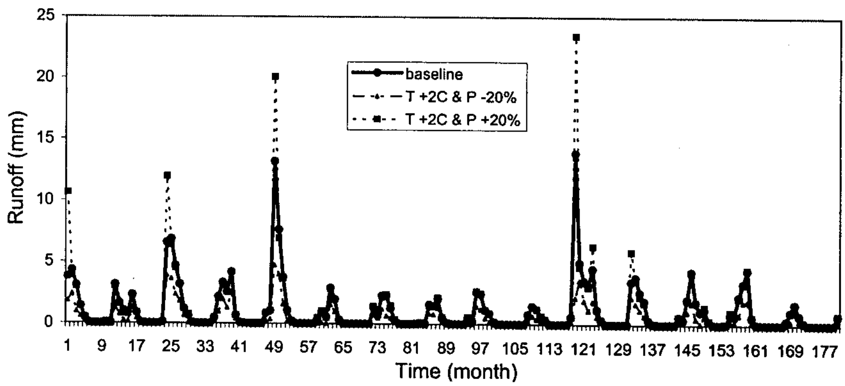


Fig. (6): Simulated monthly runoff under two incremental scenarios:

1) Temperature increased by 2°C and precipitation reduced by 20%;
2) Temperature increased by 2°C and precipitation increased by 20%.

The percent changes of annual mean runoff as a function of temperature and precipitation changes are shown in Figure (7). The largest change in annual runoff occurred when combining a +4°C with a –20% change in precipitation. These results are similar to those reported by other researchers in the Middle East. For the most critical incremental scenario (+4°C and –20% precipitation), the mean annual runoff would decline to about more than 70% of the current level. For the incremental scenarios with temperature change from +2°C to +4°C and precipitation reduced by 10%, the annual runoff will be deceased from about 40 to 60%. With decreasing precipitation the effect could be critical, particularly during long and extreme droughts. However, for incremental scenarios with temperature changes from +2°C to +4°C, and precipitation increased by 10%, the annual runoff shows a decrease from 10 to 30%. For example, for the incremental scenario with +4°C and 10% increase in precipitation, the runoff will decrease by about 30%. The annul runoff in the Zarqa River basin will increase to approximately 20% under the incremental scenario in which the temperature +2°C and precipitation increased by 20%.

The temperature and precipitation changes as predicted by the Hadley and MPI models revealed that the mean annual runoff will be reduced to about 12% and 40% respectively. Annual average values do not fully describe runoff changes for climate change scenarios. The annual distribution for various climate change scenarios should also be considered. Figure (8) presents the dynamic changes in mean monthly runoff at the Zarqa River basin for observed conditions (baseline scenario) and Hadley and MPI climate change scenarios are presented in Figure (8).

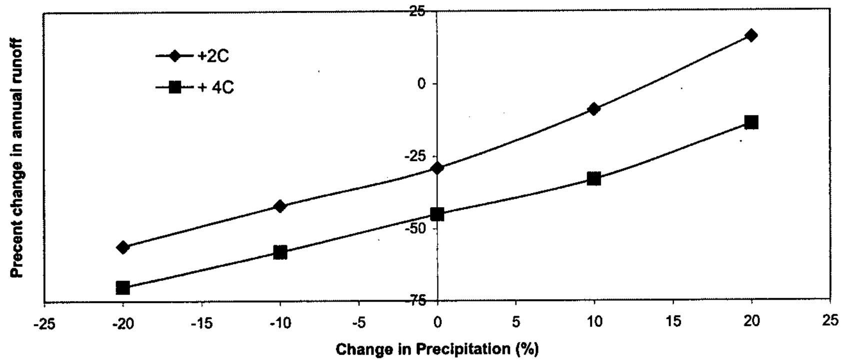


Fig (7) Annual runoff changes under the different incremental scenarios

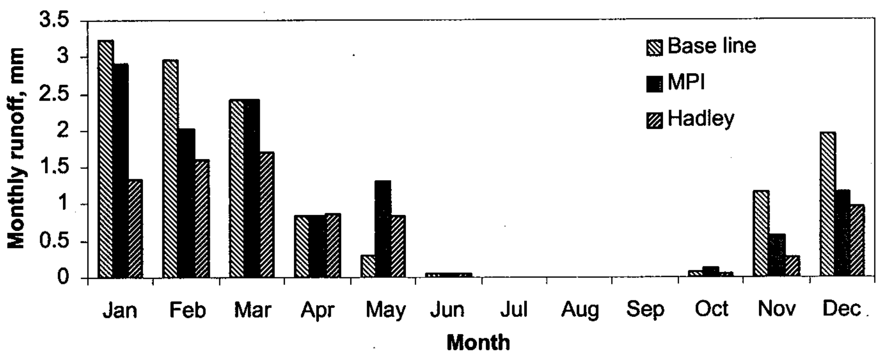


Fig. (8) Comparison between baseline mean monthly runoff and those simulated under generated climate change scenarios of Hadley and MPI models

Summary and Conclusions

The impact of the climate change on water budget components mainly monthly runoff was evaluated using the proposed procedure that consists of conceptual rainfall runoff model, and application of climate change scenarios (GCMs and incremental scenarios). The procedure was applied to the Zarqa River basin (a semi-arid basin), Jordan. The Surface-inFiltration-Baseflow (SFB) water balance model was used for simulating the monthly runoff. Seven years of meteorological and hydrological data are used for calibrating the model. The global optimization technique known as shuffled Complex Evolution (SCE) method was used to obtain the optimal parameters of the SFB model. The model performed well for the Zarqa River for which the coefficient of determination was 0.78. The average monthly runoff compared well to the observed runoff. The error of the observed and simulated streamflow is within acceptance limit and found to be around 18 percent. The model performance in the validation stage is reasonable and comparable to those of the calibration stage.

The climate changes were imposed with twelve hypothetical scenarios. Two of these scenarios were based on the predictions of general circulation models (GCMs) namely Hadley and MPI models. The other ten scenarios are incremental scenarios associated with temperature increased by +2C and +4C and changes in precipitation of 0%, +10%, +20%, -10%, and –20%. These scenarios were used as a basis for observing causal relationships among runoff, air temperature, and precipitation. Both sets of climate change scenarios resulted in decreases in monthly runoff. Also, the timing of the peak flow is not changed but the magnitudes of these peaks are reduced. Differences in hydrological results among all climate cases are due to wide range of changes in climate variables. For example, the GCM scenarios for 2x CO2 obtained from the Hadley and the MPI models resulted in similar possible future river flows. Both models showed that the increase in temperature would reduce the monthly runoff for the rainy season except for April (no change) and May (increase). The overall trend indicated that mean annual runoff will be reduced by approximately 12% (in case of Hadley Model) and 40% (in case of IMP model).

The largest change in annual runoff (reduced by 70% of the current level) occurred when combining a +4°C with a –20% change in precipitation. These results are similar to those reported by other researchers in the Middle East. For the incremental scenarios with temperature change from +2°C to +4°C and precipitation reduced by 10%, the annual runoff will be deceased from about 40 to 60%. With decreasing precipitation the effect could be critical, particularly during long and extreme droughts. However, for incremental scenarios with temperature changes from +2°C to +4°C, and precipitation increased by 10%, the annual runoff shows a decrease from 10 to 30%. The annul runoff in the Zarqa River basin will increase to approximately 20% under the incremental scenario in which the temperature +2°C and precipitation increased by 20%.

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Geographical Information System Modeling of Groundwater Potentiality in the Eastern Part of Sharjah Emirate, United Arab Emirates

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GEOGRAPHICAL INFORMATION SYSTEM MODELING OF GROUNDWATER POTENTIALITY IN THE EASTERN PART OF SHARJAH EMIRATE, UNITED ARAB EMIRATES

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ABSTRACT:

Digitized grid maps on the hydrogeology, groundwater chemistry and quality, soil classification, geologic structures and drainage lines, were used along with the ArcView GIS 3.2 package to construct an analytical GIS groundwater-potentiality model for the Al Dhaid area, in the eastern part of al Sharjah Emirate in the United Arab Emirates. Cross-correlation of model's output zoned maps was performed to identify areas of high groundwater potentiality for domestic and agricultural purposes. Results of the GIS model indicate that the eastern strip of al Sharjah Emirate (Al Dhaid region) has the highest groundwater potentiality. The strip is located close to the recharge area in the Northern Oman Mountains and is dominated by intersections of the Dibba zone, Hatta zone and Wadi Ham structural trends, which seem to control groundwater-flow velocity and recharge rate. The strip is also characterized by fresh (TDS < 1500 mg/l), soft (TH < 80 mg/l) groundwater suitable for domestic uses. Results also show that the northern and southern central parts of the study area are favorable for agriculture because both areas have cultivable soil types (Calciorthids, Torrifluvents and Torripsaments-2) and shallow groundwater (< 45 m deep) of appropriate quality (TDS < 3000 mg/l and SAR < 10). Because the eastern strip and channels of major wadis in the study area have many water wells used mainly for domestic and agricultural purposes, it is proposed to minimize or even prohibit urban and industrial activities in the upstream side of these wells and assign it as a groundwater protection zone in order to secure and maintain the present supply of good-quality groundwater.

Key words: GIS modeling, groundwater potentiality, protection zones, United Arab Emirates.

INTRODUCTION

The Al Dhaid area of eastern al Sharjah Emirate in the United Arab Emirates represents a favorable site for extensive agricultural activities because it is close to the Northern Oman Mountains (30 km), which provide a reasonable and renewable amount of groundwater. However, excessive groundwater discharge compared with the limited natural recharge has led to acute aquifer depletion. The low rainfall (155 mm/yr) and high evapotranspiration (3700 mm/yr) have also contributed to an unbalanced situation, which has led to sharp decline of groundwater levels, increase of groundwater salinity, drying up of shallow wells and deterioration of groundwater quality.

The Ministry of Agriculture and Fisheries (MAF) has realized these problems and cooperated with international agencies such as the International Water Consultants (IWACO, 1986) and Japan International Cooperation Agency (JICA, 1996) in conducting intensive field surveys using geophysical, hydrogeological and hydrogeochemical techniques for assessment of groundwater resources in this region.

These surveys were concluded in 1995, but the authors have found it necessary to extend and continue field investigations and make use of recent Geographic Information System (GIS) techniques for evaluation of groundwater resources in the eastern part of al Sharjah Emirate (Al Dhaid area). For this purpose, previous and recent data were integrated to develop a comprehensive GIS model for the groundwater resources in the study area. In this model, available geophysical data, hydrogeologic measurements, results of chemical analysis of groundwater samples and soil classification, along with the ESRI GIS package, were used to: identify major geologic structures, define hydrogeologic units, characterize groundwater chemistry, assess groundwater quality and evaluate the groundwater potentiality for domestic and agricultural purposes.

The study area, which is located in eastern al Sharjah Emirate, is a part of the central agricultural region in the United Arab Emirates. It covers an area of 850 km^2 and is bounded by Longitudes 55° 50° and 56° 00 E, and Latitudes 25° 00 and 25° 23° N, extending from the Northern Oman Mountains in the east to the Fayah Mountains in the west, the northern agricultural region in the north and the Al Madam plain in the south (Fig. 1).

METHODS OF STUDY

The fieldwork involved measurement of the depth to groundwater in the MAF observation wells and private farm wells, during the period 1995-1999; collection of groundwater samples from a 100 wells; and determination of the physical parameters such as water temperature (°C), hydrogen-ion concentration and electrical conductivity (μS/cm). The authors participated in pumping-test experiments, infiltration measurements and geoelectrical and well logging surveys. The laboratory work included chemical analysis of groundwater samples for major ions (cations: Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}, and anions: CO_3^{2-}, HCO_3^{-}, SO_4^{2-} and Cl^{-}) and trace chemical constituents (F^{-}, Fe, Zn, Cu and Pb) in the Central Laboratories of the MAF. The results were presented as contour maps using SURFER computer program version 5.01. The office work aimed at presenting, analyzing and interpreting the results of field-measured data and laboratory analysis, in addition to the results of previous investigations. The data obtained from geophysical survey, monitoring of groundwater levels and chemical analysis of groundwater samples are presented on relevant charts and graphs. The GIS modeling was carried out using ArcView GIS 3.2 package (ESRI, 1996) with ArcView Spatial Analyst, under Windows NT 4.0 platform.

GEOMORPHOLOGY AND GEOLOGY

The study area is located within desert plains and wadi flats, extending from the foothills of the Northern Oman Mountains in the east to the Arabian Gulf in the west (Fig. 2). The Northern Oman Mountains occupy the eastern part of the study area and is characterised by a rugged terrain with steep slopes, ranging in elevation from 200 m to 1200 m above mean sea level. The continued down cutting has developed many stepped river terraces and formed deep grooves along the wadi courses. Most shallow wells tap the groundwater concentrated at the nonconformity surface between the Ophiolite sequence and overlying gravel. Evidence of groundwater storage in the Ophiolite mass itself is indicated by occasional seepage during the rainy season where the fractures and weathered zones are highly integrated (Alsharhan et al., 2001). The gravel plains are covered by terrace, alluvial fans and floodplain deposits. The alluvial fans extend from the foothills of the Northern Oman Mountains in the east to sand dunes in the west. Despite that the gravel plains originate from a series of older fans, present-day runoff from the Northern Oman Mountain leaves a faint indication on them. These plains are predominantly composed of coarse particles covered by thin silt layers. The sediment size is graded from large gravel in Wadi Khadrah at the foothills of the Northern Oman Mountains to coarse sand in Wadi Lamhah further down gradient. The limestone ridges of Jebel Mileiha and Jebel Fayah break the gentle slope of the plains. The sand dunes cover a rectangular area bounded to the east by the gravel plain, Jebel Mileiha and Jebel Al Fayah, and to the west by coastal sabkhas and the Arabian Gulf. The dune sand is composed of carbonate derived from shell fragments near the coastline or quartz from quartz-bearing rocks further inland. Most of the old dunes are fixed by vegetation, composed of ancient dune materials and generally aligned in an ENE-WSW direction. The recent dunes are mobile and form a series of NW-SE trending ridges. Large dunes are located in the northern part of the study area and reach an elevation of more than 200 m above mean sea level. The drainage lines dissecting the study area originate in the Northern Oman Mountain and move from the east to the west and northwest, converging into a single channel (Wadi Lamaha) that reaches the Arabian Gulf in the northwestern corner of the study area. The largest of these are Wadi Al Dhaid, Wadi Siji, Wadi Khadrah, Wadi Hamdah and Wadi Thiqebah. The drainage lines in the mountainous areas are characterized by the trellis and rectangular patterns, whereas the wadis crossing the gravel plains have a dendritic pattern.

The main geological units in the study area are the Semail Ophiolite sequence, allochthonous units and autochonthonous units (Fig. 2). The Semail Ophiolite is the largest rock unit within the study area and its major outcrops are confined to the Northern Oman Mountains. The

Ophiolite sequence represents a complete, unaltered section of the Middle Cretaceous oceanic lithosphere. The Allochthonous units overly the western edges of the Semail Ophiolite and consist of a lower melange made up of the Semail Ophiolite blocks, exotic limestones, Hayabi volcanics, Hawasina sediments, metamorphic rocks and serpentinite (Alsharhan, 1989). The autochonthonous units, mainly composed of Maastrichtian, Palaeocene and Eocene limestone with a total thickness of 600 m, unconformably overlie the Late Cretaceous allochthonous units along their eastern and western flanks. The coarse-grained clastics of the Qahlah Formation are restricted to the eastern side of the mountains. The Maastrichtian-Lower Tertiary sediments were deformed during the Eocene Period where Tertiary folds of N-S, NW-SE and E-W trends were formed as a result of reactivation of basement faults by local salt doming or regional folding (Alsharhan and Nasir, 1996).

GEOPHYSICAL INVESTIGATIONS

Three geophysical methods including gravity, electromagnetic and well logging, were applied to: delineate different hydrogeologic units, evaluate groundwater quality, study petrophysical characteristics of hydrogeologic units and define subsurface geologic structures controlling aquifer boundaries. Results revealed the presence of the NE-SW Dibba zone, ENE-WSW to E-W Hatta zone and NW-SE Wadi Ham fault trends (Fig. 2). The Bouguer anomaly calculated with the Grant and West (1965) equations indicated a general increase in thickness of the sedimentary section from 700 m in the southeastern part of the Al Dhaid area to 3500 m in the northwest. The time domain electromagnetic soundings acquired and processed by Japan International Cooperation Agency (1996) were re-interpreted in terms of resistivity, thickness and total dissolved solids of each geoelectric layer (Table 1). The borehole logs used in this study were carried out by IWACO (1986) and Japan International Cooperation Agency (1996) and include caliper, gamma ray, resistivity, neutron, density, sonic, temperature, conductivity and hydrochemistry logs. Interpretation of these logs showed that the average porosity of alluvial gravel is 35%, while the limestone porosity ranges from 20% to 40%, depending on lithology and fracturing. The decrease in fluid conductivity and temperature were noted in association with the development of secondary porosity and inflow of groundwater from the formation into boreholes. The high resistivity reflects the presence of good-quality water in the formation, while the low resistivity is attributed to development of secondary porosity. The distribution of groundwater salinity in boreholes correlates with the groundwater flow interpreted from temperature gradient and fluid conductivity.

Table 1. Results of the time domain electromagnetic survey conducted by Japan International Cooperation Agency (1996).

Geoelectric layer	Hydrogeologic unit	Thickness (m)	Resistivity (Ohm.m)	TDS (mg/l)
First and second layers	Upper aquifer	8	200 - 2000	30-2000
Third layer	Middle aquiclude	28	10 - 100	100 - 300
Fourth layer	Lower aquifer	80	2 - 100	100 - 7500

HYDROGEOLOGY AND HYDRAGEOCHEMISTRY

Results of water-wells drilling and geophysical survey indicated the presence of three hydrogeologic units in the study area: the upper free aquifer, middle aquiclude and lower confined aquifer (Fig. 3). The upper water-table aquifer has a maximum thickness of 250 m and an average thickness of 100 m, and is composed of Holocene-Neogene unconsolidated silt to gravel, consolidated gravel and calcareous sand. The middle aquiclude consists of 50 to 300 m of impervious Paleogene shale, marl, claystone and dolomite and has a low hydraulic conductivity of 10^{-5} to 10^{-7} cm/sec (Japan International Cooperation Agency, 1996). The lower confined aquifer is composed of carbonates and clastics of Maastrichtian to Cenomanian age. The aquifer is poorly productive with the exception of the intersections of the major fault zones, especially along the Dibba zone and Wadi Ham trends. Conglomerate layers of well-sorted gravel interbedded with limestone and dolomite facies form the most productive section in the lower aquifer. Unfortunately, the thickness of this layer does not exceed several tens of meters. A summary of the hydraulic properties of the upper and lower aquifers is given in Table 2. IWACO (1986) and Japan International Cooperation Agency (1996) indicated the presence of a fissured aquifer in the Al Dhaid area. Despite the high transmissivity (776 m^2/day) and storativity (0.24) of this aquifer, little is known about its distribution, thickness and mode of recharge. The natural gamma ray survey conducted by Japan International Cooperation Agency (1996) indicated the presence of 50 anomalies coincide with vertical structures affecting this fissured aquifer. The hydrogeologic condition of this aquifer needs further investigations in the future.

Table 2. A summary of hydraulic and geoelectrical properties of the aquifers in the Sharjah Emirate (Al Dhaid area), United Arab Emirates (compiled from Japan International Cooperation Agency, 1996).

Hydraulic property	Upper aquifer	Lower aquifer
Average thickness (m)	100	175
Average resistivity (Ohm-m)	75	20
Transmissivity (m^2/day)	85	51
Storage coefficient	0.004	0.0028
Specific capacity (m^3/hr/m)	3	2
Porosity (%)	40	30
Static water level (m-amsl)	19	23

The depth to groundwater in the study area ranges from 40 to 100 m below the ground surface. Several water wells in the area went dry as a result of heavy groundwater pumping during the last three decades. The hydraulic head maps of the upper aquifer for the years 1984 and 1999 show that the groundwater level decreases from 230 m in the east to 95 m in the west, indicating that the regional groundwater flow direction is from the Northern Oman Mountains to the Arabian Gulf (Fig. 4). Between 1984 and 1999, the groundwater level decreased in most observation wells as a result of excessive pumping for all purposes. The maximum decline was 45 m within the Al Dhaid city at the center of a 20 km average diameter cone-of-depression. The average hydraulic gradient is steep (0.025) along the foothills of the Northern Oman Mountains in the east, reflecting the low hydraulic conductivity of the Ophiolite sequence, and gentle (0.005) in the western region, indicating the relatively higher hydraulic conductivity of dolomitic limestone and alluvial gravel.

During the period 1996-1999, a hundred water wells were sampled for chemical analysis in order to identify the chemical characteristics of the groundwater and to evaluate its suitability for different uses (Fig. 1). The highest groundwater temperature (39°C) was measured in the center of the cone-of-depression, where a relatively higher temperature, more saline water moves upward causing this temperature anomaly. In contrast, the groundwater collected from wells within the courses of Wadi Al Dhaid and Wadi Hamdah shows lower temperatures (32°C). These wells intercept relatively cooler recharge water at it moves from the Northern Oman Mountains towards the Arabian Gulf. The groundwater in the Ophiolitic rocks has high pH, while the pH of groundwater in carbonate rocks at Al Fayah Mountains is near neutral. The electrical conductance of groundwater is low (<1500 μS/cm) in the east and along the courses of major wadis, increasing in the northwest (4500 μS/cm) and southwest (7500 μ S/cm), in the directions of groundwater flow (Fig. 5a). The high groundwater salinity in the southwest is attributed to the dissolution of sabkha deposits.

The concentration of cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) is low along the eastern front of the study area and increases towards the west and southwest, in the direction of groundwater flow. Low cations concentration also characterizes the groundwater along the courses of major wadis because they act as conduits of low-salinity recharge water moving from the recharge zone towards the discharge area. The HCO_3^- concentration decreases from 250 mg/l in the east to about 50 mg/l in the Al Dhaid city, as a result of exploitation of the near-surface, younger water in the shallow aquifer. Westwards, HCO_3^- value increases again as a result of dissolution of carbonate rocks in the Fayah Mountains. The iso-concentration contour maps show a steady increase in SO_4^{2-} and Cl^- levels from the east to the west and northwest, in the direction of groundwater flow. Dissolution of Sabkhas and evaporite deposits is responsible for high SO_4^{2-} and Cl^- contents in the groundwater of the southwestern part of the study area. High Cl^- is also associated with the upconing of more-salinity water from the lower aquifer as a result of heavy groundwater pumping in and around the Al Dhaid city. The total hardness (TH) and sodium adsorption ratio (SAR), were used as quick indicators of groundwater quality in the study area. The groundwater in eastern Al Dhaid is soft (TH <100 mg/l), while the groundwater in the northern, western and southwestern parts is hard to very hard (TH >1500 mg/l) (Fig. 5b). The SAR of the groundwater in the study area is predominantly <10, which is good for irrigation water. The groundwater in the Al Fayah Mountains has SAR >16, which is harmful to plants if this water were used for irrigation. The northeastern corner of the study area has SAR values in excess of 13 (Fig. 5c). Table 3 shows that the mean concentrations of F and Pb in the Al Dhaid groundwater are higher than the WHO (1984) and GCC recommended limits for drinking water standards.

Table 3. The concentrations of selected trace elements in the groundwater of the Al Dhaid area as compared to the WHO (1984) of and GCC countries drinking water standards.

Parameter	**Study area**			**WHO**	**GCC**
	Maximum	**Minimum**	**Mean**	**Guideline**	**Maximum level**
F^-	14	0.10	4.84	1.50	0.6 – 1.7
Fe	0.35	0	0.01	0.3 – 1	0.30
Zn	0.20	0.10	0.15	5	5
Cu	0.10	0.10	0.10	1 – 1.5	1
Pb	0.20	0.01	0.06	0.05	0.05

GIS MODELING OF GROUNDWATER POTENTIALITY

The geographic information system (GIS) is an efficient tool for studying, assessment and management of natural resources (Lang, 1998). Rofail et al. (1998) defined GIS as "an organized collection of computer hardware, software, geographic data and personal design to efficiently capture, store, update, manipulate, analyze and display all forms of geographically referenced information". In the present study, the GIS technique was used to cross correlate soil suitability map, hydraulic head maps, groundwater quality maps and geologic structures maps to assess groundwater potentiality for domestic and agricultural uses in the Al Dhaid area.

The present analytical model was carried out using the ArcView GIS 3.2 package (ESRI products) with ArcView Spatial Analyst. Two sets of data were included in the database prepared for the purpose of this study: field data and digitized data. The field data were obtained from well locations, groundwater levels, water chemistry and water quality maps, whereas the digitized data were derived from maps of soil classification, drainage basins and major structural trends. Field data, including the groundwater salinity, total hardness, sodium adsorption ratio and depth to groundwater was stored in a database of dbf 4 format. The dbf4-formatted data was transformed into point data (vector) using a unified grid, based on the soil classification map for the study area as extended coordinates for all output maps and models. Surface interpolation (raster) of an accuracy of 50 x 50 m was assigned for each data point, which were regrouped according to selected criteria into re-classed, grid-zone maps. All maps were digitized into 50 x 50 m grid data (raster) and selected layers of grid data were superimposed according to specified criteria using the cell-based modeling technique. Finally, models were constructed, based on buffering and overlaying techniques of various interrelated zoned maps.

The input data for the analytical GIS models of the Al Dhaid area is shown in (Table 4). The soil classification map shows seven soil types: Calciorthids, Torrifluvents, Torripsaments-2, Gypsiorthids, Torriorthents, Wadi Beds and Rock Outcrops (Fig. 6a). The Calciorthids, Torrifluvents and Torripsaments-2 soil types were considered as one group, which is suitable for agriculture according to the available soil types in the United Arab Emirates (Abrol et al., 1988). On the other hand, Gypsiorthids, Torriorthents, Wadi Beds and Rock Outcrops represented the second group, which was considered unsuitable for agriculture.

Table 4. Input parameters of the GIS analytical model for the eastern Sharjah Emirate (Al Dhaid area) and their applications.

Input Parameter	Range	Application
Hydraulic head	95 - 230 m	Definition of recharge and discharge areas and direction(s) of groundwater flow.
Total dissolved solids (TDS)	705 - 7,500 mg/l	Identification of fresh, brackish and saline water zones.
Total hardness (TH)	70 - 150 mg/l	Delineation of soft and hard water and evaluation of water quality for domestic uses.
Sodium adsorption ratio (SAR)	7 - 28	Assessment of the suitability of groundwater for irrigation.
Soil classification	Suitable to unsuitable	Evaluation of soil types in terms of their suitability for agriculture.
Structural trends	--	Study the impact of geologic structures on the groundwater potentiality and recharge.

The model outputs were obtained by overly of interrelated zoned maps for iso-salinity, total hardness, sodium adsorption ratio, depth to groundwater, soil types and major fault zones and drainage lines. Table 5 shows overlies of different layers, output figures, and range of variables and their aerial distribution. Model outputs define priority areas of high groundwater potentiality for domestic and agricultural purposes (Fig. 7a,b).

Table 5. Sample outputs of the Geographical Information System (GIS) analytical model for the Al Dhaid area and their aerial distribution.

Layers	Ranges	Aerial distribution
TDS and TH	TDS < 1500 mg/l and TH < 80 mg/l	The majority of the study area
TDS and SAR	TDS < 3000 mg/l and SAR < 10	The majority of the study area
Depth to water, TDS and SAR	Depth < 45 m, TDS < 3000 mg/l and SAR < 10	The northern and southern central parts of the study area
Depth to water, TDS, SAR and soil type	Depth < 45 m TDS < 3000 mg/l, SAR < 10 and cultivable soil	The northern and southern central parts of the study area
TDS, fault zones, soil type	TDS < 1500 mg/l, fault intersections and cultivable soil	The eastern strip of the study area

CONCLUSIONS

The fault systems affecting the study area are the NE-SW Dibba zone, ENE-WSW to E-W Hatta zone and NW-SE Wadi Ham line. These faults and related wadi channels act as conduits for low-salinity recharge water to move from the recharge area towards discharge area. The total domain electromagnetic survey illustrated the presence of four geoelectric layers. The upper two layers constitute the upper free aquifer, the third layer corresponds to the middle aquiclude and the fourth geoelectric layer represents the lower confined aquifer. The hydraulic heads in both aquifers indicate that the groundwater flows from the Northern Oman Mountain in the east towards the Arabian Gulf in the west and northwest. Excessive groundwater pumping for agricultural purposes during the last 15 years has created a 20 km diameter cone-of-depression centered at the Al Dhaid city. A maximum drawdown of 45 m indicates a 3-meters annual decline in groundwater level.

The groundwater salinity in the Al Dhaid area is < 750 mg/l in the northeast, 3000 mg/l in the central area, 4500 mg/l in the northwest and > 7500 mg/l in the southwest, increasing from the east to west in the direction of groundwater flow. The groundwater in the eastern strip is soft (TH < 80 mg/l), while the northern, western and southwestern parts have hard to very hard groundwater (TH >1500 mg/l). The results of GIS modeling indicate that the eastern strip of the study area has the highest groundwater potentiality for domestic and agricultural uses because it is dominated by intersections of major structural trends, which facilitate the groundwater movement and recharge. The strip is also characterized by fresh (TDS < 1500 mg/l), soft (TH < 80 mg/l) groundwater suitable for domestic uses. The northern and southern central parts of the study area are favorable for agriculture because both areas have shallow (< 45 m deep) groundwater of appropriate quality (TDS < 3000 mg/l and SAR < 10) and possess soil types (Calciorthids, Torrifluvents and Torripsaments-2) suitable for agriculture. Because the eastern strip and channels of major wadis within the study area have many groundwater production wells used for domestic and agricultural purposes, it is recommended to minimize or even prohibit urban and industrial activities on the upstream side of these wells and assign it as a groundwater protection zone in order to maintain the present supply of good-quality groundwater.

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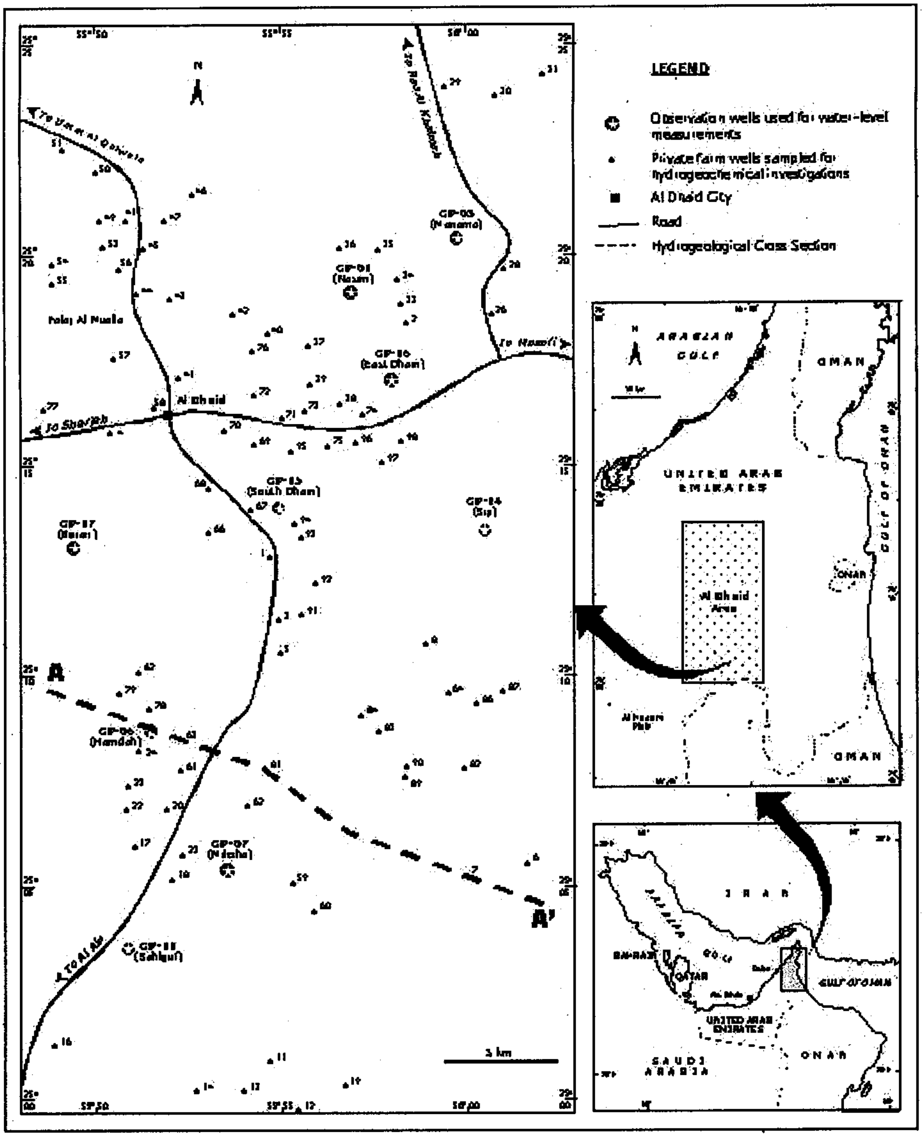

Figure 1. Location maps of the United Arab Emirates, Al Dhaid area and location of observation and farm wells sampled for chemical analysis.

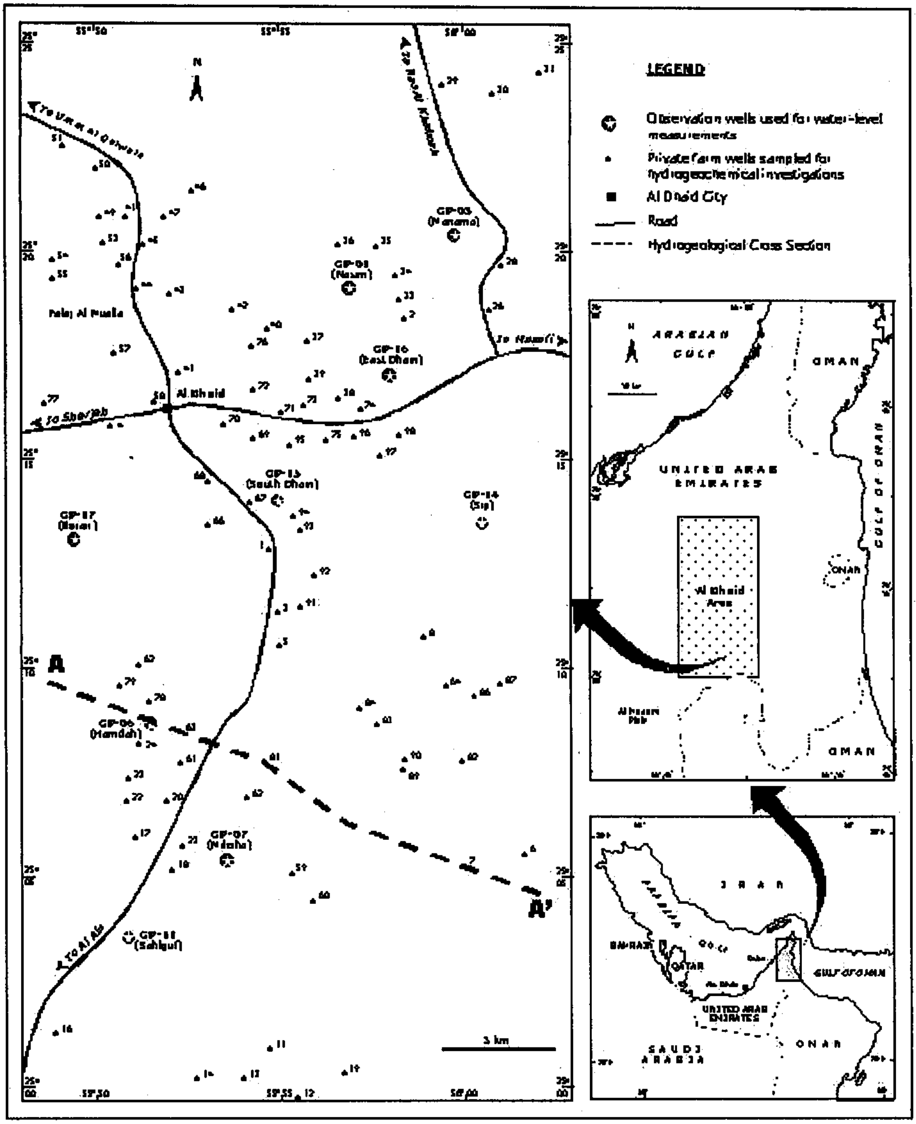

Figure 1. Location maps of the United Arab Emirates, Al Dhaid area and location of observation and farm wells sampled for chemical analysis.

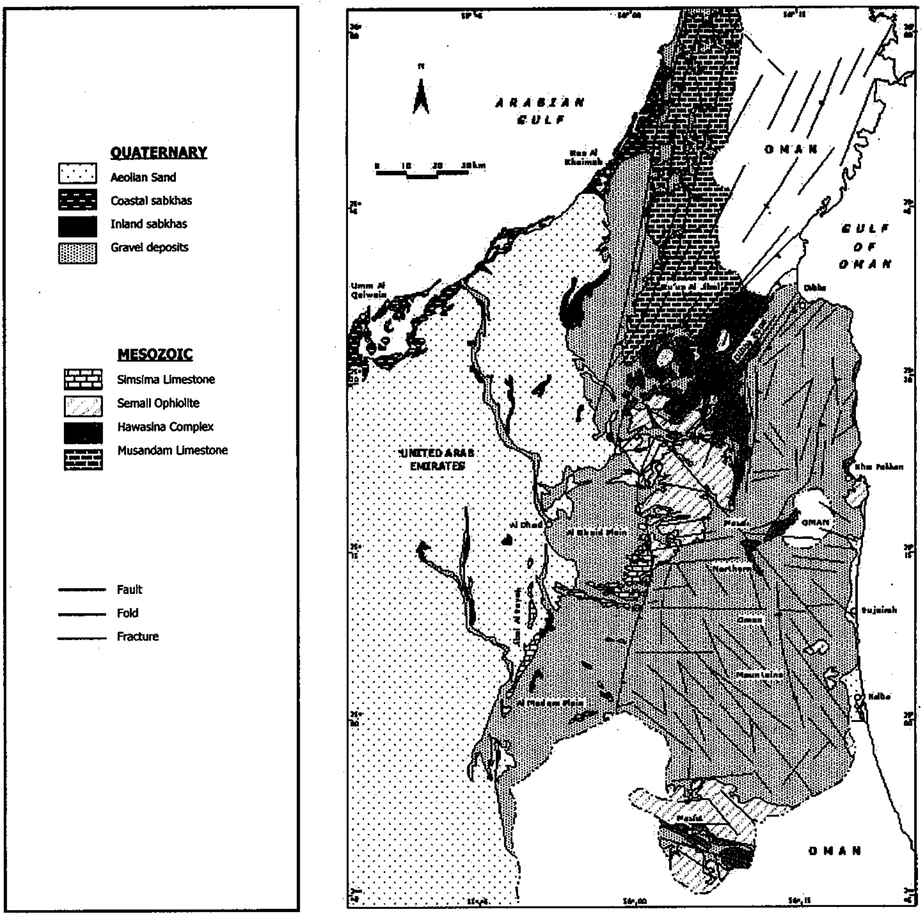

Figure 2. Geologic and main geomorphic features map of the Al Dhaid super basin and surrounding area (modified from the UAE National Atlas, 1993; and JICA, 1996).

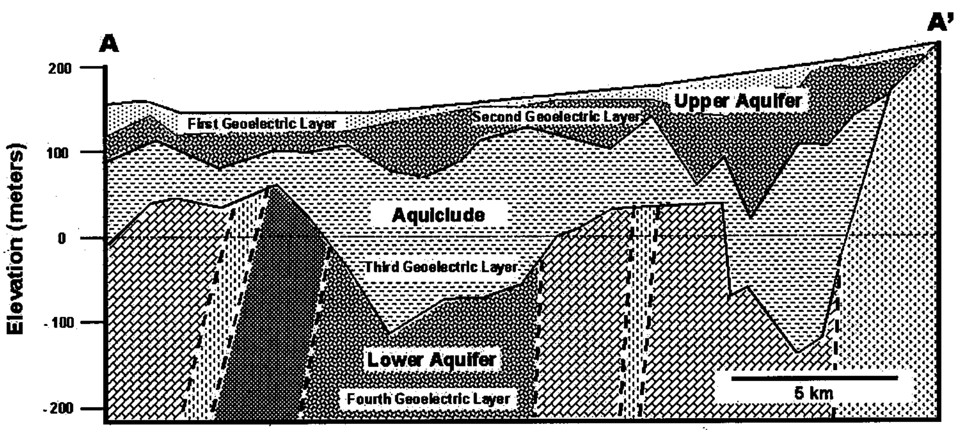

Figure 3. Hydrogeological Cross Section in the Al Dhaid area, United Arab Emirates. Location of the cross section is shown on Figure 1.

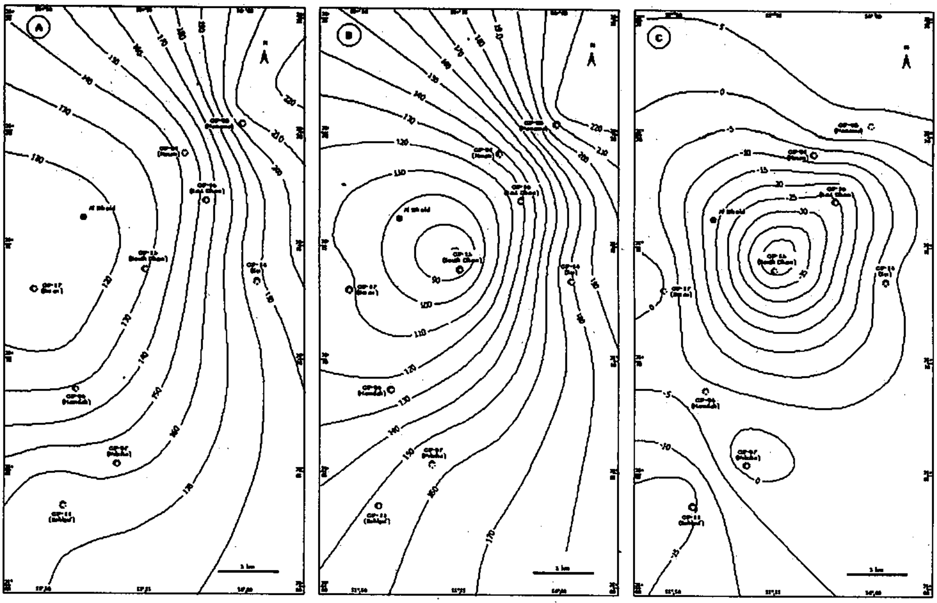

Figure 4. Hydraulic head contour map of the upper aquifer in the Al Dhaid area, in meters above mean sea level; (A) 1985, (B) 1998 and (C) hydraulic-head decline between 1985 and 1998 (modified from Al Mulla, 2001).

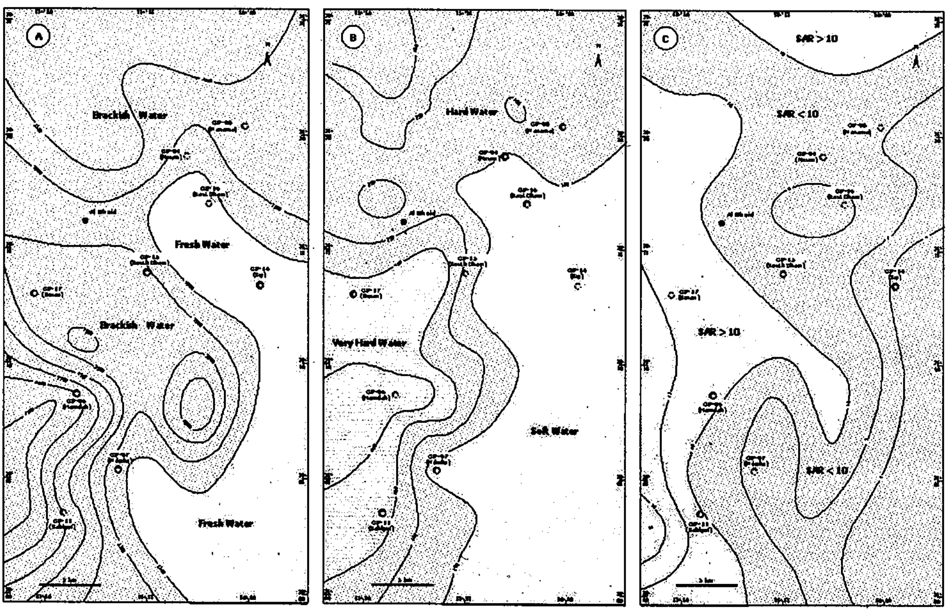

Figure 5. Iso-electrical conductance (A), hardness (B) and sodium adsorption ratio (C) of groundwater in the eastern part of Al Sharjah Emirate in January 2000.

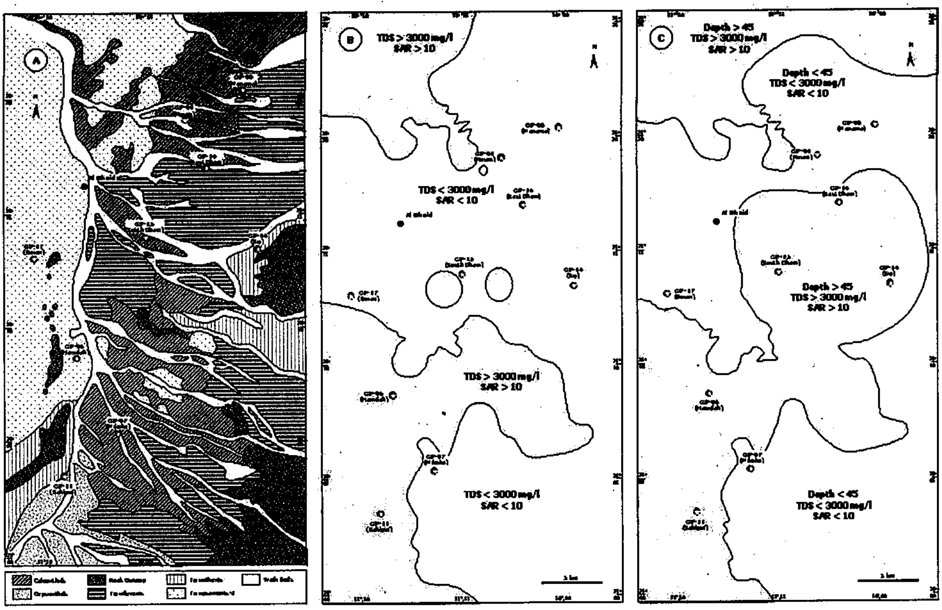

Figure 6. Soil classification map (A), suitability of water for agriculture (B) and shallow groundwater resources (C) in the eastern part of Al Sharjah Emirate in January 2000.

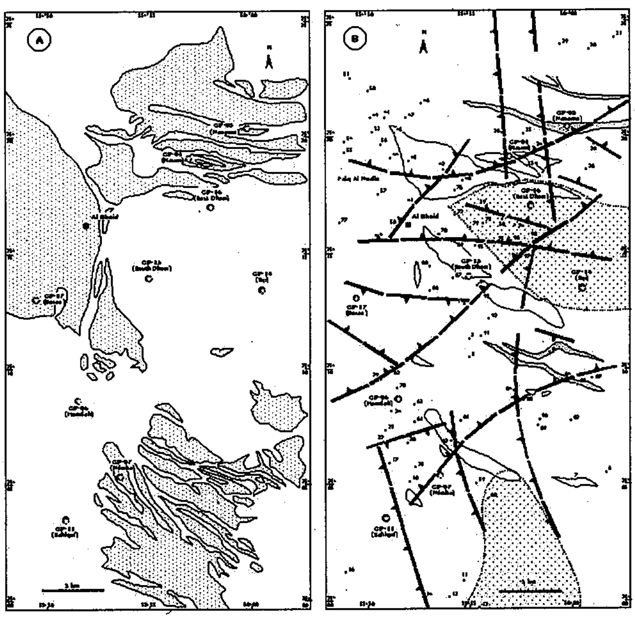

Figure 7. ⬚ Areas suitable for agricultural purposes (A), and ⬚ areas of high groundwater potentiality (B) in the eastern part of Al Sharjah Emirate in January 2000.

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