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The 7th Gulf Water Conference

WSTA Seventh Gulf Water Conference

Water in the GCC - Towards an Integrated Management

19 - 23 November 2005, State of Kuwait

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The Seventh Gulf Water Conference
Water in the GCC...Towards an Integrated Management
State of Kuwait, 19-23 November 2005

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Preface

Water is the most valuable resource on Earth. It is an important vector in the socio-economic development and for supporting the ecosystem. In the arid to extremely arid Arabian Peninsula, home of the GCC countries, the importance and value of water is even more pronounced. The GCC countries of United Arab Emirates, Bahrain, Saudi Arabia, Oman, Qatar, and Kuwait, are facing the most severe water shortages in the world. Rainfall scarcity and variability coupled with high evaporation rates have made these countries the least endowed in these resources in the world. However, the scarcity of renewable water resources is not the only distinctive characteristic of the region, inadequate management intervention and the continuous deterioration of its natural water resources have become during the past few decades equally distinguishing features as well.

In the last three decades, rapid population growth and accelerated socio-economic development in the GCC countries were associated with a substantial increase in water demands, which have escalated from less than 5 billion cubic meter (bcm) in 1970 to about 30 bcm in 2000. These demands have been driven mainly by agricultural consumptions (currently at 81% of total water used in GCC countries), and by rapid urban expansion (19%).

To meet rising demands, water authorities have focused their efforts mainly on the development and supply augmentation aspects of water resources management. Demands are being satisfied by the development of groundwater (91%), extensive installation of desalination plants (7%), expansion in wastewater treatment and reuse (2%), in addition to dams construction to collect, store, and utilize runoff. Currently, groundwater resources are being over-exploited to meet mainly agricultural water demands, which contributes less than 2% of GDP in most of these countries, and with continuous deterioration in their quantity and quality. In most of the countries, unplanned groundwater mining continues without a clear "exit" strategy and address to the "what comes after" question.

To meet domestic water supply requirement, GCC countries have turned to desalination and have become collectively the world leaders in desalination, with more than 50% of the world capacity. However, desalination remains capital intensive and costly in the region, especially that these countries do not possess this technology; while financial cost of desalinated seawater has been decreasing to around US$ 0.70 per cubic meter in the USA and other places, the average water production costs in the GCC countries remain somewhere between US$ 1 to 2 per cubic meter. In terms of wastewater treatment and recycling, the coverage rate of sewage collection and treatment system seems to be lagging far behind water supply service (20-60%), and available treated wastewaters are still not being reused to their potential and without consideration to the opportunity cost of the reclaimed water treated to a tertiary level. Although planning for full utilization of treated effluent are in the early stages, most of the GCC countries have ambitious plans for the full utilization of treated effluent.

The supply-driven approach for water management has demonstrated its inability to deliver substantial degree of water sustainability or security to the water-stressed GCC countries; despite the strenuous efforts made by these countries in this approach, they still face serious water deficits due to the continuously increasing water demands beyond the limits of their available water resources. Indeed, it is questionable if adequate supplies can be sustained in the future without heavy burden on national budget and might have expensive socio-economic impacts. In fact, the supply augmentation approach coupled with inadequate attention to improving and maximizing the efficiency of water allocation and water use have led to the emergence of a number of unsustainable water uses in these countries, such as low water use efficiency, growth of per capita water use, increasing cost of water production and distribution, and deterioration of water quality as well as land productivity. The situation was further aggravated by the lack of comprehensive long-term water policies and strategies that are based on supply-demand considerations, and was further compounded by the institutional weaknesses, fragmentation and overlap of water agencies, and inadequate institutional capacity building and enabled society.

As pressures on water converge on the region's water resources, the need for innovative approaches in water management becomes more apparent and quite urgent. The international community has recognized this fact, and over the past decade a consensus had been formed on integrated water resources management (IWRM) as an appropriate approach to address threats posed to water resources and to ensure its sustainability. Within the framework of sustainable management of water resources, IWRM takes into account a broad spectrum of social, economic, and ecological factors and their links. Effective coordination and participatory decision-making process are insured throughout IWRM. IWRM process depends on collaboration and partnerships at all levels, from individual citizens to international organizations, based on a political commitment to, and wider societal awareness of the need for water security and the sustainable management of water resources. To achieve IWRM, there is a need for coherent national and regional policies to overcome fragmentation and lack of good governance.

Fortunately, all the GCC countries have realized that efficient development and management of water resources requires water policy reforms, with more emphasis on demand management measures and improvement of the legal and institutional provisions. In essence, appropriate water sector policy reform should address the key issues of reliable assessment of water supply and demand, water quality deterioration and protection, water use efficiency and allocation, role of the private sector, pricing policies and cost recovery, groundwater mining, stakeholder participation, improved institutional support, food security and the increasing problem of water scarcity. Water policy reform needs to address these key issues, taking into consideration the specific requirements and the prevailing social, economic, and cultural conditions of the GCC countries.

Addressing the immense challenges associated with water resources management requires daring reforms to existing institutions and policies governing water resources. Far reaching and multi-sectoral approaches will be critical if we are to overcome inefficient use of water resources and make their use sustainable. This will require the establishment of a proper enabling environment that ensures the rights of users and provides the appropriate level of protection for the resource. Policies, legislation, establishment of governing bodies at various levels and knowledge management are all part of ensuring that the objectives of IWRM are met. The Seventh Gulf Water

Conference was intended to be a landmark in the water resources management in the GCC countries and to lay the foundation of IWRM policies and strategies in these countries.

As at the previous WSTA conferences (Dubai, 1992; Bahrain, 1994; Oman, 1997; Bahrain, 1999; Qatar, 2001; Saudi Arabia, 2003) the overall goals of the Seventh Gulf Water Conference are to encourage scientific studies and research in the different fields of water resources, to create a forum of open discussion and exchange experiences among the Gulf States that the WSTA engendered through the six previous conferences.

The objectives of the convening conference are: 1) Review and assess the progress made in the GCC countries towards the internationally agreed on target of adoption and implementation of comprehensive policies and strategies for integrated water resources management and their active implementation (WSSD, Johannesburg, 2002); 2) Identify main issues, challenges, constraints, as well as opportunities and lessons learned in the implementation of IWRM for sustainable development in arid regions with special reference to the GCC countries and its prevailing socio-economic, political, and environmental conditions; 3) Assess current status of natural and non-conventional water resources in the region in relation to present and future water demands in the GCC countries; 4) Promote and encourage a shift in the region from the supply-driven approach to the demand-centered and conservation approach within the framework of IWRM; and 5) Promote the development of a research and development strategy for the water sector in the region with special reference to the enhancement of existing and new technologies for water desalination and wastewater treatment and their role in enhancing water supply.

The Seventh Gulf Water Conference was held under the patronage of His Highness Sheikh Sabah Al-Ahmad Al-Sabah, the Prime Minister of the State of Kuwait, and is organized by the Water Science and Technology Association (WSTA) in cooperation with Kuwait Institute for Scientific Research (KISR) and the Secretariat General of the Cooperation Council (GCC) for the Arab States of the Gulf. The Conference was sponsored by the Ministry of Energy, Mohammed Abdulmohshin Al-Kharafi & Sons W.L.L, Kuwait Shell Limited, Kuwait Foundation for the Advancement of Science (KFAS), Prince Sultan Bin Abdulaziz International Prize for Water, National Water Technology, COMSTECH, Environment Public Authority (KEPA), UNESCO Cairo Office, Arab Center for Studies in Arid and Dry Lands (ACSAD, Syria), United Nations Environment Program (UNEP/ROWA), and United Nations Economic and Social Commission for West Asia (ESCWA, Lebanon). The Conference was supported by the Arabian Gulf University, Food and Agricultural Organization (FAO/RNA, Egypt), Arab Organization for Agricultural Development (AOAD, Sudan), International Atomic Energy Agency (IAEA), International Center for Biosaline Agriculture (ICBA, Dubai), United Nations University (UNU), European Desalination Society (EDS), International Desalination Association (IDA), and the World Bank (WB).

This conference proceedings contains 102 papers assembled into three volumes, one volume in Arabic (15 papers) and the other two in English (87 Papers). The conference papers were selected by the Conference Scientific Committee from over 150 abstracts received from the conference call of papers. Many of these were modified to meet the standards of the Scientific Committee review. The conference papers were reviewed by 42 regional and international water science and technology experts, with each paper reviewed by two reviewers. The final editing of the conference papers were made by Dr. Waleed Al-Zubari (AGU), Dr. Meshaan Al-Otaibi (KISR), and Dr. Amjad Aliewi (HEW, Palestine). Twenty five papers were invited from GCC water-related government agencies, supporting organizations and renowned regional and international experts to give scientific presentations in respective technical sessions. Conference sessions will be held on 10 topics: Water Resources Management and Planning; Development and Management of Conventional Water Resources (Groundwater and Surface Water Resources); Municipal Water Management; Domestic Wastewater Treatment and Reuse; Public Private Partnership; Water, Health, and Environment; Water and Agriculture; Desalination and Treatment Technologies; and Water Management in the Oil Industry.

The Scientific Committee wishes to express its deep appreciation to the Government of the State of Kuwait and Kuwait Institute for Scientific Research (KISR) for hosting and organizing the conference, and the many Kuwait, regional, and international conference sponsoring agencies, organizations, and companies, who kindly supported and endorsed this conference by providing their generous funds, keynote speakers, and political support.

Organization of the Gulf Water Conferences requires considerable time and effort. As in the previous WSTA conferences, individuals from various sectors (industry, government, and academia) have come forth and given generously their time. Special thanks are due to the members of the Organizing Committee and the Scientific Committee, and Scientific Papers Reviewers.

Finally, the Scientific Committee wishes to acknowledge the immeasurable contributions made by the authors and their research associates who were not only willing to rework and modify their manuscripts, but also had to meet an extremely tight time schedule. Without their efforts this document would not have been possible. We sincerely hope that this conference will achieve its objectives and is both enjoyable and rewarding for you.

Prof. Dr. Waleed K Al-Zubari
Chairman, Conference Scientific Committee
Vice-Dean, College of Graduate Studies
Arabian Gulf University

TABLE OF CONTENTS

WATER RESOURCES PLANNING & MANAGEMENT

DEVELOPMENT AND MANAGEMENT OF NATURAL WATER RESOURCES

b) Surface Water Resources

The 7th Gulf Water Conference
مؤتمر الخليج السابع للمياه

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WATER RESOURCES PLANNING & MANAGEMENT

Challenges and Opportunities in Implementing Integrated water resources management (IWRM) in ESCWA Member Countries

Roula Majdalani

CHALLENGES AND OPPORTUNITIES IN IMPLEMENTING INTEGRATED WATER RESOURCES MANAGEMENT (IWRM) IN ESCWA MEMBER COUNTRIES[1]

Roula Majdalani
Water Issue Team, Escwa, Lebanon

ABSTRACT

The formulation and application of integrated water resources management (IWRM) plans in ESCWA member countries requires the creation of an enabling environment, the definition of institutional roles, and the mobilization of effective management instruments which can appropriately address the specific environmental, social, economic and institutional conditions prevailing these countries. To this effect, all ESCWA member states, have adopted the Johannesburg plan of Implementation (JPOI) which calls on all participating countries to develop and implement IWRM strategies by 2005 and achieve water efficiency. However a review of the progress made by ESCWA countries has showed mixed results. Different countries are adopting different approaches in reforming their to national water sector which reflect important differences in their socio-economic and cultural conditions and in their legal and administrative systems.

Many factors affect the effectiveness translating and applying IWRM concepts and principles to the national and local levels, which notably include: High population and urban growth, Growth in economic activities and expansion in construction projects, Unsustainable modes of water uses, Weak institutional set-ups in the water sector, Limited awareness of IWRM concepts and policy implications, and Conceptual gaps in IWRM framework.

ESCWA reviewed progress made by member countries to formulate and implement water strategies based on IWRM framework. In this respect a survey was undertaken in 2001 and another in 2004 to quantify and qualify the progress made by member countries in that respect. After analysis member countries were categorized into three different categories according to the level of IWRM implementation achieved. The three categories identified were as follows:

- Category 1: Countries that formulated national strategies for the implementation of IWRM (Egypt, Jordan, Palestine and Yemen)
- Category 2: Countries that are in an advanced state of national strategy formulation (Bahrain, Kuwait, Qatar, Saudi Arabia and United Arab Emirates)

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[1]This paper is a summary of ESCWA report on "Framework for Implementing IWRM National Strategies in the ESCWA Region (forthcoming – 2005)

- *Category 3:* Countries that have prepared studies or applied IWRM programmes at the local or basin level or that have applied policies that are in line with the concept and guidelines of IWRM (Iraq, Lebanon, Oman and Syria)

The survey showed that all ESCWA countries have approved the principles and concept of IWRM and are in the process of incorporating IWMR components in their national water strategies. However these countries are at different stages of application or formulation of plans or have followed different institutional, legislative and organizational approaches to the issue. Additionally the different economic and social characteristic of each country influenced the means and ways these strategies are formulated and later on applied. However all ESCWA member countries are facing many challenges on the application level. This situation raises concern over several issues that decision makers need to address in order to correct and activate these strategies. The main issues identified are as follows: Investment plans and resource mobilization, Application of laws and regulations in water management, Capacity building plans, Activation of all modes of partnership, Monitoring and managing change, Water governance within IWRM framework.

Overview

In their effort to promote IWRM plans, ESCWA[2] member countries adopted the Johannesburg Plan of Implementation (JPOI) for the sustainable management of their scarce natural resources. All member countries agreed to formulate and implement national strategies for the application of Integrated Water Resources Management (IWRM) guidelines by the year 2005. While all adopted the general principles and guidelines of IWRM framework (see figure 1); each country proceeded to develop its own water sector policies and strategy according to its own priorities and conditions. A review of the progress made by these countries has showed mixed results. Different countries are adopting different approaches to national water sector reform that reflect important differences in their socio-economic and cultural conditions and in their legal and institutional set-up. The biggest challenge facing ESCWA member countries lies in striking a balance between the need for tangible and short-term solutions to meet pressing demand on scarce and overused water resources and adopting sustainable strategies that control and regulate water use and safeguards the needs of future generations.

There are a number of factors, which influence the effectiveness, and feasibility of implementation of IWRM guidelines in a coherent and consistent manner particularly when it involves medium to long-term planning cycles. While every country in the ESCWA region has its specificity in this regard, there are a number of common regional characteristics, which affect the IWRM implementation process these include: i) High population and urban growth rates, ii) limited concern for "sustainability" in the economic and development policies adopted so far; iii) Trade-off between food security vs. water security, iv) Limited awareness of the "integrated" and "management" dimensions of IWRM: and v) Gaps in applied research on IWRM.

Hence, guided by its mandate to support member countries' efforts in promoting IWRM application and formulation of national IWRM strategies by 2005, ESCWA initiated surveys in 2001 and in 2004 to evaluate the progress made by member countries in formulating and implementing their IWRM national strategies. The surveys adopted a self-evaluating approach to check how each country perceived its achievements, priority needs and challenges in implementation. The answers/responses were cross-referenced with country reports on water demand management policies and field surveys undertaken by staff members to some of these countries in addition to reports published by the concerned ministries on the issue (see Annex A for the results of the 2004 survey).

The assessment indicated that all ESCWA member countries are reviewing their national water strategies within the IWRM framework, and are formulating necessary institutional, organizational and legal measures in conformity with the planned strategies. However, very few countries completed these strategies and integrated them into social and economic development frameworks to achieve a good level of sustainable development. Coordination among concerned ministries, notably ministries

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[2]The Economic Commission for Western Asia (ECWA) is part of the secretariat of the United Nations and its membership covers 13 countries in the region , namely Bahrain, Egypt, Iraq, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, United Arab Emirates and Yemen.

of agriculture and environment, was not up to the expected level, which suggests that the enabling environment to apply IWRM is not yet in place. The mobilization of resources to activate integrated institutional reforms and the application of relevant, coherent and feasible management tools for IWRM also gave mixed results among ESCWA member countries and within these countries. Even when the results of the survey indicated that a given country was at an advanced stage of applying IWRM guidelines, some important aspects of IWRM framework lagged behind notably in relation to the participatory approach needed, cost recovery and private sector participation in water projects.

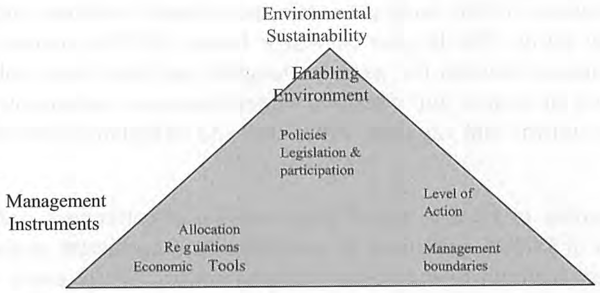

Figure 1: The IWRM General Framework

Additionally most of the surveyed countries expressed their need for intensive, effective and enhanced capacity building programmes, mainly at the managerial level. The expected roles of all stakeholders involved in the application of IWRM should be clearly defined. In particular, the role of the public sector in terms of monitoring, coordination and the responsibility for creating an enabling environment should be well articulated so that all concerned parties (water users associations, water authorities, consumer associations, civil society and private sector) are able to manage and enhance their participation in an efficient and transparent manner. Based on the results of the survey and analysis of relevant material, Member countries were grouped in three different Clusters according to the level of IWRM implementation achieved with respect to (a) measures to ensure that an enabling environment prevails; (b) steps towards to implementing institutional reforms and (c) adopting relevant management tools. The Clusters identified consist of the following:

- *Cluster A:* Countries that completed their national strategies for the implementation of IWRM (Egypt, Jordan, Palestine and Yemen)

- *Cluster B:* Countries that are at an advanced stage of formulating their national strategies (Bahrain, Kuwait, Qatar, Saudi Arabia and United Arab Emirates)

- *Cluster C:* Countries that have prepared studies or applied IWRM programmes at the local or basin level or that have applied some policies that are compatible with the concepts and guidelines of IWRM (Iraq, Lebanon, Oman and Syria)

These proposed categories reflect the approach adopted by member countries in conceiving, developing and applying their IWRM strategies. They are by no means indicative of any ranking, showing level of advancement. A literal comparison among countries can in fact be misleading. Any relevant comparison should be drawn from within the country, where progress has been in one component of IWRM, (e.g. developing an enabling environment) over another area (e.g. defining institutional roles).

1. Cluster A: Egypt, Jordan, Palestine and Yemen

Countries in this cluster are at an advanced stage in formulating and implementing national water strategies compliant with IWRM guidelines and concepts. These countries have reformed their organizational structures and adopted institutional and managerial measures to apply IWRM guidelines. Some commonalities in their water situation, economic and social characteristics, and water consumption are identified which can explain similarities in the way water resources are managed and means used to protect the quality and quantity of these resources and consequently, leading to similar IWRM process in the four countries.

The most common characteristic with respect to IWRM is the *Political Will* to apply a sustainable water management strategy. In this respect, the four countries undertook a series of studies and policy briefs for the formulation of their national water management plans. These studies comprised thorough assessment of the water situation, current and forecasted water demand, investment needs including legal and financial means needed to mobilize private sector investment. Major progress is noted in articulating the legal framework to regulate the water quality, protect the environment, control water use and establish local and sub-regional water authorities to manage water and sanitation services in all four countries.

The preparation of national strategies involved noticeable stakeholders' consultations through workshops and town hall meetings involving decision makers, water users associations, representatives from the irrigation sector, private companies and local communities. Donors played a supportive role in consolidating these strategies, by providing the technical and financial support to undertake necessary studies, training and plan formulation which allowed a better understanding of IWRM concepts and policy implications. They also encouraged the countries to develop implementation and investment plans identifying existing and potential resources and means for mobilizing funds from private sector and international agencies.

Institutional arrangements were another area where these countries registered progress. They managed to consolidate most water related departments under one ministry or institution responsible for water resources planning, management and distribution. However, the main differences remain over the management of irrigation and the environment sectors.

Capacity building to enforce new or reformed institutional roles usually proved to be the weakest link and often hindered the effective application of national IWRM strategies. Training workshops for this purpose are held on ad hoc basis and instigated by donors and international agencies. The shortcomings in capacity building programmes are not due to shortage of funds per se, but rather in the capacity to ensure the sustainability of these programmes and match them with the actual institutional reforms needed to ensure that trained personnel are retained in the public sector institutions.

However, these countries scored high with respect to issues related to the management of shared water resources and conflict resolution. This is understandable given that all countries in this Cluster rely on shared water resources. These countries have a good standard of qualified national capacity in negotiation on legal, technical, political and economic aspects of water management.

Box 1: Summary of major accomplishments and challenges in the application of IWRM in: Egypt, Jordan, Palestine and Yemen

Major Accomplishments:
Political decision- Integrated water strategy- Water quality laws- Environment protection plans- Investment plans- Formulation of policies and work plans in negotiation skills and water demand management- Water reuse technologies- Cost recovery schemes.

Challenges:
Law enforcement- Mobilization of resources/ local capital- Rationalization of water use in the agriculture sector- Political situation (mainly in Palestine) that limits ability for long term planning and implementation of water plans

Areas in need of improvement to enhance IWRM application
Resource mobilization to reform and improve the water sector- Expands and improve the efficiency of water and sanitation services- Institutional set-up- Participatory approach- Private sector participation- Intensify use of treated and recycled water.

1. Cluster B: Bahrain, Kuwait, Qatar, Saudi Arabia and United Arab Emirates

Countries in this cluster display similarities in their national water strategies, in line with IWRM concepts and guidelines. Their environmental, economic and social conditions greatly affect the way IWRM plans are formulated and applied. Rapid economic growth coupled with high rates of population growth and urbanization (4-6% in population growth between 2000 and 2005 and more than 88% of urbanization) have led to major demographic shift, in a short time span with significant impact on patterns of water consumption and management. Rapid growth is paralleled by ambitious development plans aiming at increasing economic activity, notably agriculture in the context of promoting food security policies and providing their citizens with high standards of urban services. These services included new water and sanitation infrastructures whereby more than 85% of the population has nowadays access to water and sanitation services and good quality of water. Increasing demand for water, especially from groundwater resources which are the main source of water in these countries, has resulted in its overexploitation to levels beyond the recharge levels and hence dependency on the production of unconventional sources of water such as desalinated and treated wastewater to balance the demand-supply deficit.

Aware of the need for sustainable patterns of water consumption and development strategies, all five countries have embarked on reforming their water sector, focusing on rational use of available water resources, and balance it with on-going projects to increase water production. In their efforts to create an enabling environment to apply IWRM concepts and guidelines, Bahrain for example has prepared a water plan for

2006-2020 and reassessed all available resources and future water demands. This reassessment exercise helped in drawing future water policies to manage this vital sector and identify gaps in legislation related to the development and protection of water resources. In Saudi Arabia the ministry is preparing a national strategy and action plan for the water sector that includes an assessment of the current water management practices (developed in 2005), development of strategic water policies (in progress) and development of an action plan to execute the water strategy (expected in 2008). Qatar is currently reviewing and modernizing its legal framework to apply IWRM guidelines and concepts, and is while the United Arab Emirates has adopted a legal framework, which regulate the management of water supply and sanitation sector (Law enacted in 2002), building on its successful experience in public-private-partnership in providing water and sanitation services.

The five countries also reformed their institutional frameworks, whereby an independent Ministry is now responsible for the management of water resources. This type of institutional setting separates the management of water resources from its sectoral use. Planning, management and enforcing legislation are under the responsibility of one Ministry that in turn will serve all sectors without bias towards one sector over the other. This type of institutional and legal set-up facilitates public – private partnership in the provision of water and sanitation services, which these countries have a good record of. Furthermore, the simplification measures introduced in customer services and computerization and developments in the management of information systems are noticeable in these countries, notably UAE, Qatar and Bahrain, although coordination among various concerned departments still need further improvements and speeding-up.

At the level of developing and applying management tools of IWRM, the five countries have a good record of partnership with the private sector, and scored high on this item in their replies to the survey, particularly in terms of water desalination and water reuse treatments. The UAE for example started to formulate a long-term privatization plans through BOO projects for the provision of water between various international companies and different water authorities, and regulated by the Regulation & Supervision Bureau. In Saudi Arabia, several attempts were made to enhance the participation of the private sector, thus motivating the ministry of water and energy to improve and develop the management of this sector. In this respect, a two-phase managerial plan was put into place. Phase one focused on implementing demand management measures which include installing water meters, invoicing and collecting revenues. Phase two focused on a general reform of the water sector with emphasis on new operational and legal frameworks and a thorough review of tariffs. As for Qatar, a Permanent Water Resources Committee (PWRC) was established in April 2004. This Committee is concerned with proposing general policies and formulating strategies for water projects, as well as prioritizing the execution of implementation and recommending budget allocation to relevant authorities.

Box 2: Summary of major accomplishments and challenges in the application of IWRM in: Bahrain, Kuwait, Qatar, Saudi Arabia and UAE

Major Accomplishments:

Framework for private sector participation - Efficient consumer services – Institutional set-up- Legal Framework- Capacity to enforce- Improved water infrastructure and efficiency- Water reuse.

Challenges:
Food security within the sustainability context- Importance of water balance and integration for effective IWRM application- Economic tools (water services cost recovery- pollution fees) – involve civil society in water issues

Areas in need of improvement to enhance IWRM application
Rationalization of water use, with emphasis on the agriculture sector- Water Demand management – Cost recovery (at least part of cost) – Enhance partnership with civil society.

1. Cluster C: Iraq, Lebanon, Oman and Syria

Countries in this cluster have similar experience with respect to progress in the application of IWRM guidelines. The application of IWRM is experimental and undertaken at a pilot scale, at the basin level or local level, although Oman has taken concrete steps towards developing their national strategies. Countries in this cluster have adequate water supply from surface water mainly and groundwater resources with the exception of Oman, where the arid environment is the main cause of water scarcity. The agriculture sector is the main water using sector, ranging between 58.% in Lebanon and 96% in Oman, while agricultural efficiency varies from highest in (e.g. Iraq) the region to low return (e.g. Oman). However, though these four countries do not have the same economic, social, political and environmental conditions, they have shown in their responses common factors in their management of the water sector, namely their diversified and considerable experience in managing their resources at the local or basin level. However in order to scale-up these initiatives to the national level or replicate them in other regions of the country, there is a need for a comprehensive national framework linking them in a coherent and integrated manner in order to achieve any visible and long-term impact for sustainable use of water resources.

The weak political commitment to reform the water sector with all what it implies in terms of formulating integrated executive plans, investment plans and updating and strengthen legislation and enforcing them (e.g. controlling) well drilling in agriculture areas in peri-urban areas where urban sprawl takes place without the supporting basic infrastructure. Thus, it is hard to motivate people to rationalize their water consumption and to cooperate and coordinate among themselves at the local level if the enabling environment is not well in place. We cannot however ignore that many plans and projects to manage and develop the water sector are undertaken within the IWRM framework, like a national strategy for promoting water demand management in Oman, public-private partnership in Lebanon, and the establishment of basin management committees in Syria. It should also be noted that survey result indicate that 2 of 4 counting consider they have IWRM plans.

As for the reorganization of the organizational framework to enhance water management efficiency, all four countries have undertaken steps towards this end. Syria established independent water directorates at the basin level as a step towards enhancing decentralization and promoting effective roles for local water authorities. Iraq also established a new ministry for water resources to integrate all water using sectors. In Lebanon, new responsibilities were given to the new ministry and four water authorities to manage the water sector including the formulation of water policies and project implementation. The ministry of regional municipalities, environment and water resources in Oman promotes the decentralization of the management in its work. Within this ministry, the general directory for water issues implements water development projects and works on modernizing and improving its services. All four countries also undertook capacity building programmes for their technical personnel, however national capacity in management skills, coordination and cooperation at institutional levels still needs further support. With respect to the application of management tools in IWRM, most of these countries consider that their capabilities in assessing and monitoring their water resources and needs are good and do not necessarily need further capacity building in this area. However the biggest challenge remains in data collection, its reliability, timeliness and the development of appropriate indicators to monitor various aspects of IWRM application at national and local level. Other management tools such as water services pricing and, pollution tariffs are still areas in which these countries should dwell on given the resistance to this issue by powerful interest groups.

Finally, countries in this Cluster (Syria, Iraq and Lebanon) scored high on issues related to negotiation skills and conflict resolution. All four countries share their water resources with one or more riparian countries. Lebanon and Syria have made considerable progress in this field where they signed several cooperation agreements for the Al-Kabir and Orontes River, including plans to build a common dam. Management of shared water resources in these countries and ESCWA member region in particular is first and foremost an issue in the political realm and is considered a matter of national security.

Box 3: Summary of major accomplishments and challenges in the application of IWRM in: Iraq, Lebanon, Oman and Syria

Major Accomplishments:

Decentralization and water management at the basin level- Integrated management at the basin level (Aflaj system in Oman) – Agreements on shared water resources use (Lebanon and Syria).

Challenges:

Lack of detailed water strategies and investment plans- poor water and sanitation infrastructure and services-

Enforce water related legislation- Activate institutional and legal frameworks- Enhance role of joint committees to manage shared water basins- Build and maintain dams and water quality monitoring

Areas in need of improvement to enhance IWRM application

Rationalization of water use- Capacity building- Enhance partnership approach- Formulate realistic and applicable water strategies including assessment studies, investment plans and definition of roles.

4. Beyond 2005: Framework for strengthening national IWRM plans

ESCWA countries have endorsed the WSSD/JPOI and adopted the principles and concepts of IWRM and are in the process of incorporating IWRM components in their national water strategies. Variation in economic and social characteristics of each country influences the means and ways these strategies are formulated and later on applied. However in most cases the challenges lies in securing the political will to put plans into action, enforce legislation, "manage" the process, "integrate" and coordinate across sectors, and above all commit to a participatory approach to ensure that good water governance prevails. Hence ESCWA member countries.

(a) Develop/finalize national water strategies in line with IWRM guidelines and that translate the current water situation in the country and means for sustaining these resources. Several ESCWA countries could serve as models for other countries in this respect and could provide guidance and the methodology to other countries. (e.g. Yemen and Jordan).

(b) Complement these national plans with detailed investment plans, based on thorough assessment of the water resources and formulate strategies/plans to mobilize resources to implement all these plans, indicating available and potential resources, schedule of implementation and potential source of funding

(c) Review current national legislation and local legal practices with respect to water use, drill, etc.. Each country/area may have different cultural practices and may hinder any law enforcement plan put in place by the government regarding water resources. It is very important to integrate these practices, or at least to understand them before enacting and trying to enforce any new legislation that could be thought of as "imported"

(d) Building the capacity of concerned technical personnel and decision makers. Capacity building is considered an integral part of IWRM, whereby an enabling environment needs the proper technical skills and institution set up to be effective. Furthermore building capacity increases aptitude to achieve the sustainable management of water resources.

(e) Encourage multi-level dialogue (bottom-up, top-down, horizontal , etc, see Annex B). Activate all modes of partnership to encourage an IWRM oriented civil society and effective participation of all stakeholders. This leads to shared water visions, joint diagnosis, creation of favourable grounds for joint implementation and monitoring

5. Activating stakeholders partnership for implementing and sustaining IWRM

(a) Identify the partners concerned from the different sectors and their potential contribution at different stages of preparation/ implementation of national IWRM strategies

(a) Define the legal framework that regulates the private sector participation in investment projects

(a) Strengthen decentralization through capacity building programs for water authorities, basin committees, municipalities, agricultural cooperatives and water users associations

(a) Organize national workshops at regional/basin levels to discuss proposed national strategies and action plans for the participation of different categories of stakeholders

(a) Define and develop the modes of partnership: Negotiation & and conflict resolution skills at national level, awareness plans, discuss methods for defining performance indicators.

ANNEX A

Results of ESCWA 2004 survey on Member Countries progress in implementing IWRM national strategies (see footnote 1)

IWRM toolbox	Lebanon	Saudi Arabia	Kuwait	Palestine	Iraq	Yemen	Bahrai n	Oman	Jordan	Syria	Egypt	Qatar	UAE
A-Enabling Environment													
A1. Policies. Setting goals for water use, protection and conservation													
A1.1 Setting National Policies	2	2	2	3	2	3	1	3	3	2	3	3	2
A1.2 Policies with relation to water resources	2	2	2	3	2	3	2	3	3	3	3	3	2
A2 Legislative framework. Water policy translated into l													
A2.1 Water rights	2	1	1	1	1	2	3	2	2	3	2	2	1
A2.2 Legislation for water qual		2	2	2	2	1	3	3	3	3	2	2	1
A2.3 Reform of existing legisla	2	2	1	1	2	2	3	2	2	3	3	2	1
A3- Financing and incentive structures													
A3.1 Investment Policies	2	1	2	1	3	2	2	2	2	3	2	2	3
A3.2 Financing options: I Grants& Internal sources	2	2	2	1	3	3	2	2	2	3	2	2	1
A3.3 Financing options: II Loans & equity	1	1	2	2	1	1	1	1	2	1	3	2	3
A3.4 Cost recovery and chargin prices		1	1	2			1	1			2	2	2
A3.5 Investment appraisal	1	1	1	1	2	2	1	1	2	2	3	2	2

B Institutional Roles													
B1 Creating an organizational framework													
B1.1 Transboundary organizatio water resource management	2	2	1	2	1	2	1	2	2	2	2	2	1
B1.2 National apex bodies	3	3	1	2	3		2	2	3	2	1	2	1
B1.3 River basin organizations	1		1	1	3	2			2	3	2		
B1.4 Regulatory bodies and enforcement agencies	1	1	1	1	1	1	2	2	2	2	2	3	1
B1.5 Service providers and IWR	2	2	1	2	2	1	2	2	3	2	2	3	2
B1.6 Civil society institutions an community based organizations	1	1	1	2	1	1	1	2	2	2	2	2	1
B1.7 Local authorities	2	1	1	2	2	2	2	2	2	2	2	3	2
B2 Building institutional capacity													
B2.1 Participatory capacity and empowerment in civil society	1	2	1	2	2	1	2	2	2	1	3	3	2
B2.2 Training to build capacity i water professionals	2	2	1	2	2	1	2	2	2	1	3	3	2
B2.3 Regulatory capacity	2	1	2	1	1	1	2	2	2	1	2	3	2
B2.4 Knowledge Sharing	2	1	2	2	2	1	2	1	2	1	2	3	2

C. Management Instruments													
C1. Water resources assessmen													
C1.1 Water resources knowledge base	2	2	1	3	2	1	3	2	2	1	3	3	2
C1.2 Water resources assessmen	2	3	1	3	3	2	3	2	3	2	3	3	2
C1.3 Modeling in IWRM	1	2	1	3	3	1	1	2	3	1	2	3	2
C1.4 Developing water resources indicators	1	2	1	2	3	2	2	2	2	2	2	3	1
C2 Plans for IWRM													
C2.1 National IWRM plans	1		1	1	2	2			2	2	2	-	-
C2.2 Risk assessment and management	2		1	2	2	2	2	2	2	1	2	3	1
C3 Efficiency in water use													
C3.1 Improved efficiency of use	2	2	1	2	2	1	2	2	3	2	3	3	2
C3.2 Recycling and reuse	1	2	2	2	1	1	2	2	3	2	3	3	2
C3.3 Improved efficiency of wat	2	2	2	2	2	2	2	2	2	2	3	3	2
C4- Social change instruments													
C4.1 Education curricula on wat management	3	2	1	2	1	2	3	2	3	2	1	2	3
C4.2 Communication with stakeholders	2	2	2	2	2	2	3	3	2	2	2	3	3

C4.3 Information and transparen awareness raising	2	2	1	2	2	1	2	3	2	1	2	2	3
C4.4 Communication with stakeholder	1	2	1	2	2	1	2	2	2	1	2		2
C4.5 Water campaigns and awareness raising	2	2	2	2	1	1	2	2	3	2	3	2	2
C4.6 Broadening participation in water resources management	1	2	2	2	1	1	1	2	3	2	3	3	2
C5 Conflict resolution													
C5.1 Conflict management	2	1	1	1	2	2	1	3	2	2	2	-	1
C5.2 Shared vision planning	2	2	2	1	3	1	1	2	2	2	3	-	1
C5.3 Consensus building	2	2	1	1	3	2	1	2	2	2	3	-	1
C6 Regulatory instruments													
C6.1 Regulations for water quali	3	2	2	2	2	2	2	3	3	2	2	3	2
C6.2 Regulations for water quantity	2	2	2	3	3	1	2	2	3	2	2	3	1
C6.3 Regulations for water services	2	2	2	3	2	2	2	3	2	2	2	3	2
C6.4 Land use planning controls and nature protection	2	1	2	1	3	1	2	3	2	2	2	3	2
C7 Economic instruments													
C7.1 Pricing of water and water services	1	2	1	2	1	2	1	1	3	2	2	3	2

C7.2 Pollution & environmental	1	2	1	1	2	1	1	2	1	1	2	1	2
C7.3 Water markets and tradable permits	1	2	1	2	1	1		1	2	1	1	3	2
C7.4 Subsidies and incentives	2	2	2	1	2	1	1	2	2	2	2	-	2
C8- Information Exchange													
C8.1 Information management system	1	2	2	2	1	2	2	2	3	2	2	2	2
C8.2 Sharing data for IWRM	1	2	2	2	1	2	2	2	2	2	2	2	2

Numbers 3: satisfactory implementation
Number 2: some progress in implementation
Number 1: Not initiated or limited progress in implementation

Note: Countries listed in the table are those that have responded to the questionnaire

ANNEX B

Stakeholders participation in IWRM

IWRM components	Water Ministries	Water utilities	Basin committees/ Joint committee for shared water resource management
The Enabling Environment	Enacting Legislation on Water rights/water quality Preparation of national plans Agreements Preparation of national water strategy Investment policies & strategy Design framework for the private sector participation	□Develop cost recovery and tariff application mechanisms □Network/ encourage private companies investment in utilities projects Establish WA steering committees of local	Integrated development and investment plans for the basin Mechanisms for cooperation at inter-ministerial level/ cooperation on shared water Set institutional, legal & operational framework for basin management/ project implementation
Institutional Roles	Support a partnership-based/ multi-stakeholders water management system Strengthen the regulatory bodies and enforcement	□Build capacity of WA water professionals on IWRM, esp. regulation enforcement and customer services Network & knowledge sharing among water utilities □& support best practices □Ensure participation of local community reps/ NGOs in policy setting and planning & design	Capacity building on negotiations over shared water resources Develop knowledge sharing mechanisms among riparian
Management Instruments	Assess national water resources & demand projections Monitor regulatory bodies on water quality, quantity and distribution networks/ service efficiency	□Monitoring water quality, distribution and services □Ensuring proper metering and tariff application □Tradable permits	Water resources Assessment Prepare, coordinate and implement shared water projects Shared-vision planning Consensus building

IWRM components	Private operators/ Private investors	Civil society (NGOs, professional associations, unions)	Water User Associations
The Enabling Environment	❑ Technical consultation with related stakeholders (WA.ministries) related to operation & maintenance contracts	❑ Advocacy to reform legislation/ institutional structure to ensure participation ❑ Ensure citizen/ CS participation is included at early stages of IWRM plan formulation	❑ Develop mechanisms to cooperate with farmers, NGOs. Citizen groups, WA ❑ Participate in developing agricultural policies , water allocation for irrigation & water saving policies ❑ Support women participation and empowerment within WUA
Institutional Roles	❑ Identify/ assess existing technical/ management support capacity measures for defining roles and responsibilities	❑ Identify stakeholders their agenda, mode of operation and capacity to participate in IWRM ❑ Support knowledge sharing and best practices initiatives among CS organizations	❑ Discuss, clarify and disseminate information on intuitional role, responsibilities and functions of WUA in different stages of IWRM planning process
Management Instruments	❑ Training and CB on Technical aspects of water management ❑ Improve water service delivery through innovative water technologies	❑ Organize water campaigns and awareness raising Campaigns to support gendered perspective of IWRM Develop/ implement training/ CB at community level	❑ Devise cooperation mechanisms among WUA members to implement and maintain irrigation networks Setting standards and monitoring mechanisms for improving water distribution to stakeholders

IWRM components	Media	Donors
The Enabling Environment	Devise media strategy for clarifying why & how IWRM is every body□s business Prioritise water issues and IWRM as issues of national concern & as □news□ items Disseminate stakeholders and citizens□ views and concerns on water and IWRM strategies & mode of implementation to decision-makers	Support national governments in preparing/ developing national IWRM strategies through a consultative and participatory process Provide technical support and knowledge sharing on means for initiating legislations and institutions reforms for IWRM
Institutional Roles	Participate in capacity building initiatives and knowledge sharing on means for effective implementation of redefined/ reformed institutional roles in IWRM	Support capacity building and knowledge sharing, provide resource material, training manuals, online support, e.discussion forums on IWRM issues and policy implications Coordinate cooperation between countries on the river basin level and shared water
Management Instruments	Support training and capacity building programs through dissemination of audio-visual material, documentary films, etc. on importance of water conservation and IWRM applications	Develop capacity building and training of trainers programs Support knowledge sharing, networking and dissemination of best practices Train water professionals on project formulation for technical and financial support from donors

Integrated water resources management setting the stage

Evan Vlachos

INTEGRATED WATER RESOURCES MANAGEMENT
SETTING THE STAGE

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ABSTRACT

Mounting concerns about the environmental impacts of human activities, potential climatic shifts, expanding populations and demands as well as new knowledge are part of the pressing need to develop alternative institutional schemes for managing in an integrated manner scarce natural resources. Many nations have increasingly been turning attention to both streamlining existing administrative mechanisms and to introducing innovative institutional arrangements with regard to quantitative and qualitative aspects of the management of their water resources. In the context of conceptual, methodological regulatory and administrative developments particular emphasis is placed on the need for integrated approaches; the mobilization of resources, personnel and facilities; and in incorporating new or emerging professional practices and technological innovations to traditional water management approaches.

This backdrop of concerns, trends, developments and "crises" of complex interacting forces is further magnified in urban settings where size, density and scale of operation produce explosive rates of growth and unique spatial patterns; excessive economic costs for infrastructure expansion and maintenance; extensive management problems and the search for organizational coordination; complex environmental challenges and ecosystemic considerations; and larger problems of national (even international) developmental policies. Thus, the need for new configurations of water management systems. Such complex systems involve also the interaction of numerous public, private and non-profit groups, each having conflicting and competing interests, as well as demanding problems of jurisdiction and cross-sectoral issues of complex environmental perturbations.

All the above remarks point out that in the last four decades a series of themes have emerged in the search for "integrated," "holistic," "comprehensive," or "total" water management. There has been a convergence of issues, concerns and developments that transformed approaches to planning and management from "Feasibility", elitist studies of the 1960s, to a foresight emphasis and "polluter pays" principle of the 1980s, through the sustainability, normative emphasis of the 1990s, to finally, the search and preoccupation with "global", integrated approaches at the beginning of the 21st century.

1.0. The Changing Water Scene

The last 30 years are characterized by significant changes in the planning, design, and management of water resources all over the planet. Mounting concerns about the environmental impacts of human activities, potential climatic shifts, expanding populations and demands as well as new knowledge are part of the pressing need to develop alternative institutional schemes for managing in an integrated manner scarce natural resources. Many nations have increasingly been turning attention to both streamlining existing administrative mechanisms and to introducing innovative institutional arrangements with regard to quantitative and qualitative aspects of the management of their water resources. In the context of conceptual, methodological regulatory and administrative developments particular emphasis is placed on the need for integrated approaches; the mobilization of resources, personnel and facilities; and in incorporating new or emerging professional practices and technological innovations to traditional water management approaches.

Thus, rapid socio-economic changes during the last quarter of the 20th century underscore the need to address a wide array of environmental challenges, articulate the premises of a desirable sustainable development, and promote comprehensive approaches as well a combination of structural and non-structural responses to persistent water resources problems. A large and fast increasing literature has explored all over the world the plight of adequate and safe water, the difficulties for sustainable development of water resources, as well as the continuous efforts to introduce and apply systematic, interdisciplinary approaches in water resources planning and management. Implicit in all such discussions are also a number of more general considerations regarding the present and future of water resource development. The often-repeated concept of *sustainability* reflects not only the increasing environmental awareness at the end of the 20th century; but, also, the search for new and balanced paradigms of socio-economic development. Management of water resources should not only be socio-economically significant but also cost effective and efficacious in the long run. The maintenance of ecosystem integrity through multiple uses and the balance of national, regional, as well as basin-wide demands is based on considerations of both intra- and inter-generational equity as well as involvement of local populations in insuring effective and implementable water resources action.

A series of trends and developments constitute the backdrop of an imminent crisis regarding water supplies and their utilization. Factors underlying this context of urgency include: a) the high variance of water supply in many parts of the planet, resulting in dramatic fluctuations, exacerbated by periodic droughts or floods; b) rapid population growth and significant consumptive demands, especially as a result of dramatic shifts from rural to urban areas; c) expanding agricultural uses and intensive irrigation developments; d) deterioration of water quality, result of both intensive agricultural practices and of urban and industrial uses; e) decreasing groundwater availability coupled with contamination of a large number of aquifers; f) increasing environmental concerns and ecosystemic considerations, including natural changes and the entire gamut of anthropogenic disturbances in the surrounding environment; and g) transfrontier water dependencies, and challenging questions of overlapping and shifting political and administrative boundaries affecting shared water bodies.

Another way of looking at long lists of concerns and conflicts linking sustainable development and integrated water resources management is through a cross-cutting list of interacting issues and "crises" that includes:

- A water supply and demand crisis that represents a predominantly engineering dimension. Here one should include management and population growth issues such as the promotion of more desirable levels and patterns of use; augmenting fresh water supplies through e.g. conservation, reuse, desalination, transport of water from other areas; conjunctive water use with withdrawals from aquifers, reservoir storage, etc.
- A deteriorating water quality crisis that can be translated into an ecological dimension of water problems. Here one encounters a variety of health issues, poor water quality, waterborne diseases, lack of adequate safe drinking water supplies and sanitation qualities, groundwater contamination, as well as interference of water resources systems with the proper functioning of natural life cycles.
- A transboundary dependencies crisis representing in many cases a geopolitical dimension not only in terms of international boundaries but also intra-national transfers of water across administrative boundaries (as e.g. in such volatile situations as in Cyprus or the Western Bank cities).
- An organizational crisis exemplified in a management dimension, i.e., the appropriate mix of competent personnel, facilities and procedures, as well as legal imperatives and administrative guidelines. The literature refers here to "capacity building" and to the fact that the people who can best manage a system effectively and efficiently are those who know what an urban water system is supposed to accomplish and understand how it functions.
- A data and information crisis, not only in terms of availability, validity, reliability or comparability but also as part of combining data and judgment, modeling, and the building of useful Decision Support Systems.
- A "perceptual" crisis representing societal understanding of the nature and extent of water and other environmental crises, preoccupation with the negative consequences of human impacts on the surrounding environment, and the urgency to respond to underlying deeper socio-economic causes of what are now outlined as symptoms of global apprehension of developmental imbalances.

This backdrop of concerns, trends, developments and "crises" of complex interacting forces is further magnified in urban settings where size, density and scale of operation produce explosive rates of growth and unique spatial patterns; excessive economic costs for infrastructure expansion and maintenance; extensive management problems and the search for organizational coordination; complex environmental challenges and ecosystemic considerations; and larger problems of national (even international) developmental policies. Thus, the need for new configurations of water management systems. Such complex systems involve also the interaction of numerous public, private and non-profit groups, each having conflicting and competing interests, as well as demanding problems of jurisdiction and cross-sectoral issues of complex environmental perturbations.

An example of useful approaches here has been that of integrated urban water system (IUWS) introduced in the 1960s and 1970s as part of the Urban Water Resource Research Program in the U.S. In this approach the most pressing challenges of the 21st century revolve around five clusters of concern, namely resources and their conservation; infrastructure expansion, improvement, innovation and integrated design; the re-introduction of water in the city as an amenity, aesthetic presence, and recreational element; institutional improvements in terms of public participation, organizational mobilization, and water legislation and standards; and last, but not least, a "new thinking" or a mind-set, if you wish, of a willingness and daring to move beyond traditional approaches and to conceive and apply new solutions to complex urban water problems. This concept of Integrated Urban Water Management is a culminating point of past developments and of the central role of the 1992 Rio Summit. Yet, while developed countries have been using coordination, area-wide integration, cooperative management, and functional integration of water services, in developing countries the challenge is much greater. Here limited centralized water and sewerage, fragmented services, environmental assaults, absence of funding, and rapidly expanding populations, all starkly contrast to the noble vocabulary of integrated management and sustainable development.

2.0. Managing in Turbulent Times: Shifting Paradigms

All the above remarks point out that in the last four decades a series of themes have emerged in the search for "integrated," "holistic," "comprehensive," or "total" water management. There has been a convergence of issues, concerns and developments that transformed approaches to planning and management from "Feasibility", elitist studies of the 1960s, to a foresight emphasis and "polluter pays" principle of the 1980s, through the sustainability, normative emphasis of the 1990s, to finally, the search and preoccupation with "global", integrated approaches at the beginning of the 21st century. Some selected themes of this convergence and preoccupation with IWRM result among others from a) *conceptual breakthroughs*, including shifting paradigms in terms of ecosystems, sustainability, heterarchization, complexity, uncertainty, turbulence, and interdependence of surrounding environments: b) *methodological advances* especially multi-purpose/multi-objective approaches, Decision Support Systems, Risk Analysis, and the implications of rapidly expanding computational prowess; c) *organizational mobilization,* in terms of new administrative mechanisms, institutional arrangements, renewed interest in river basins contingency planning, Alternative Dispute Resolution etc.; and, d) *contextual changes,* signifying the entire gamut of on-going and future quantity and quality problems, new areas of concern, shifting priorities, as well as potential socio-political intervention mechanisms and comprehensive natural resources policies. Cross-cutting such areas or themes have been such additional issues as the challenge of subsidiarity, accountability and transparency, pricing mechanisms for public goods, public awareness involvement and participation, transboundary interdependencies, emerging water intensive lifestyles, climate change and extreme hydrologic events, and so on. But above all, studies upon studies have zeroed onto a larger water governance crisis, characterized by sectoral approaches, top-down institutions, fragmentation, and, inefficient, misguided public projects.

It is obvious, then, that IWRM exemplifies the promise of how to deal with complex water issues in an efficient, effective and equitable manner. But simple as such an "integration" promise may seem, it is at the same time, full of difficulties as to its definition and implementation. Indeed, the reaction to the shortcomings of traditional water and other resources planning has brought forward a series of improved planning and management processes and approaches. They include such related notions as Participatory

Planning, Action Planning, Comprehensive Planning, and Strategic Planning. Such approaches include also such noticeable characteristics as cross-sectoral coordination and integration, interdisciplinary approaches, linkages to and from national polities, normative orientation, extensive public participation, mechanisms for conflict resolution, regular monitoring and evaluation, as well as futures-oriented approaches. This new planning and management horizon reinforces the premises of sustainability, reflects new paradigms and practices, and exemplifies the challenges and opportunities for innovative approaches in water resources management. The connotation of the world "integrated" has evolved slowly, representing the broadening scope of water resources management. "Integrated" goes beyond traditional coordination among agencies, or interactions between water uses, or planning approaches which consider all possible strategies and impacts. Integrated water resources management is an integral part of a region's social and economic development. In such a broader context, key concepts and dimensions essential for an integrated approach include, sustainable development, sectoral integration, demand management, capacity building, and public participation.

Thus, the definition provided by the Global Water Partnership in 2000 [TAC#4] as "IRWM is a process which promotes the coordinated development and management of water, land and related resources in order to maximize that resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems," stands as a succinct summary of recent writings, declarations, or directives that attempt to explain component parts of IWRM.

In reading this literature and following current practices, we see a preliminary outline of the emerging paradigm of IWRM. There seem to be four critical parts in this tentative "model" or paradigm:

A. PRINCIPLES (philosophical premises), which represent the wide gamut of water declarations all the way from the Mar del Plata Conference (1977), to the pivotal conclusions of the Conference on Water and the Environment in Dublin (1992). The last underlines in particular the finite and vulnerable character of freshwater, its essential nature as an economic good, and the participatory approach in planning and management.

B. Overriding CRITERIA & STANDARDS which exemplify the search for valid and reliable indicators around the key concepts of economic efficiency (including true cost recovery); ecological sustainability (or ecosystemic integrity); and, social equity (fairness or justice).

C. CROSS-CUTTING PRACTICES, representing the operational context of IWRM in terms of:
   a) basin-wide/watershed emphasis;
   b) integration of supply and demand approaches;
   c) intersectoral coordination, combining users and uses as well as authority and responsibility;
   d) regulatory and institutional frameworks for integrated policies;
   e) special consideration of transboundary interdependencies and geopolitical factors; and,
   f) equitable access to water through participatory and transparent governance.

D. MANAGEMENT AND IMPLEMENTATION ASPECTS, emphasizing both organizational re-arrangements in terms of vertical, horizontal, interdisciplinary, functional, and stakeholder integration; and, the consideration of such implementation mechanisms as the creation of an enabling environment, institutional mobilization, and specific management instruments.

3.0. What Do Such Developments Imply?

Combined with the increased emphasis on sustainability, the response to the forces of social changes and the cry for integrated water management, imply first of all an alternative vision of the means by which ecologically sustainable and socially just communities will emerge. Equally important, they challenge us as to how can we conceptualize and institute water management mechanisms across different socio-cultural settings, or introduce diversified experiences of responding to the forces of rapid social changes in increasingly expanding megacities. In essence, we are being asked to confront growth and development differently. Water authorities are asked to move from a commitment to protecting and regulating environmental quality to the more complex commitment to sustainable development where water management strategies should incorporate the central notion of the finite nature of water ecosystems; the need for an ethos of conservation; changing technologies (for both innovation and renovation); a predominant political institutional context; and, changing goals that recognize multi-purpose, multi-objective and multi-disciplinary approaches.

This paradigm shift, responsive to complexity, intergenerational equity, balanced ecosystem principles, and economic efficiency permeates current writing and practices of water management. Water resources systems development has an obligation to see that those systems provide sufficient quantities and qualities, at acceptable and fair prices, while at the same time protect the environment and preserve the health of ecosystems for future generations. What is important at this point is the repeated emphasis on *justice* and *equity* and the normative character of all such efforts attempting to describe "fairness", duty to posterity, changed life-styles and similar notions of broad environmental policies. This implies the centrality of goals and objectives, an extended time horizon, institutional mobilization or, in other words, policies and expressed goals to be measured eventually by relevant indicators. In essence, what has changed in recent years is our understanding of implementing a coherent set of water management measures which correspond to broader planning principles and encompassing policies. Rather than beginning with "optimal" answers or solutions to perceived water problems, we now start our planning by asking what are the objectives for management and the broader goals of sustainable development.

If this is the drift of the emerging paradigm, one can better understand a "visionary" strain in recent policy initiatives (see e.g. the pronouncements of the Hague 2000 Conference and the challenging underpinnings of the Water Framework Directive of EC). Many of the water issues that appear at the beginning of the 21st century include items that have been of concern to planners for many years (such as adequate water supply, groundwater quality, provision of safe water, etc.); while others are of more recent origin (such as nonpoint source pollution, adequate instream flows for fish, "commodification" of water, participatory planning, etc). What has been strongly recognized, is the widely shared perception that water resources problems cannot be solved without taking into account the complex interrelationship of technical, social, political economic or environmental factors.

What all the above indicate, is that we must consider new conceptual, methodological, and organizational responses in managing complexity and uncertainty of fast changing and transforming water resources systems. The literature across many countries has produced long lists of comprehensive approaches; coordination mechanisms; stakeholders involvement; local and regional responsibility and accountability; sustainability principles and environmental ethics; decision support systems and risk management; long-range, macro-engineering emphasis; and, innovative approaches in trade-off considerations. The vocabulary of policy formulation, management, and implementation, entails fundamental changes in outlook, visionary and goal-oriented commitment, as well as acceptance of the central premise that social, technical, economic and environmental problems are intertwined and must be resolved together. In the dynamic context, of today's societies there must be not only a better perception and understanding of water related conflicts; but, also, more pragmatic policy initiatives for devising means for preventing and solving water related conflicts as well as new institutional structures to better handle aggregate competing and conflicting water demands.

Thus, the end result and long-term commitment of an integrated management approach involves:

a) the capacity for environmental scanning (monitoring trends and developments);
b) organizational mobilization in terms of improved and responsive management;
c) development of Decision Support Systems (DSS) in order to promote relevant implementable action; and,
d) contingency planning through a richer menu of options and a wider range of alternatives.

There are, obviously, inherent dilemmas in addressing the variety of complex water systems, especially in the rapidly expanding megacities of our world. These dilemmas are the result of multiple objectives, of expanded geographical scope and of conflicting and competing demands and choices. Yet, there is a discernible convergence into three main themes:

a) The need for <u>new paradigms</u> that would incorporate increasing preoccupation with sustainability, social indicators of development, and ecosystem maintenance; the shift from multi-disciplinary integration; a perceived transformation from crisis (reactive) to risk (proactive) management; and imaginative approaches of heterarchical (non-linear) considerations rather than exclusive preoccupation with hierarchical, linear systems.

b) The understanding of <u>new contexts,</u> reflecting complexity and rapidity of change (or what some futurists have been summarily describing as "raplexity"); new transfrontier regimes, globalization and interdependence; global change and climatic anomalies requiring new conceptual models and theoretical propositions; and, different modeling approaches and shifting social values.

c) The emergence of new methodologies, addressing cumulative, synergistic, diachronic impacts and consequences of natural and human factors; emerging Decision Support Systems (such as GIS and Expert Systems) that combine data, information and judgment as well as knowledge, experience and common sense; the benefiting from rapidly increasing computational prowess and new complex multi-factorial models; improved risk assessment and vulnerability analysis; integrated, holistic, comprehensive, heterarchical management schemes, network analysis and organizational mobilization; and, anticipatory scenarios, contingency planning, and expanded policy options.

Essentially, there is a need for establishing a broader perspective and interdisciplinary approaches, especially in urban water management. Such perspectives and approaches would enable us to account for the variety of environments affected by water development by considering more disciplines; by incorporating an extended horizon in our thinking; and by concerning ourselves with the far reaching consequences of human actions in the surrounding environment. The last points out also that there much be a fundamental shift from a prevailing reactive crisis management approach (short-range preoccupation and immediate technological fixes) to a more anticipatory risk management that allows us to concentrate on contingency planning and reasonably foreseeable futures. We should consider the development of a new "social calculus" which would enable us not only to meet present exigencies, but also to consider the meaning of our actions in the context of long-range plans and preferable futures.

Water ethics perspective in the Arab region

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WATER ETHICS PERSPECTIVES IN THE ARAB REGION*

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ABSTRACT

Water ethics has only recently emerged in academic and development arenas as an independent field of professional discussion. Concerns over water conservation and adequate access to basic needs of water and sanitation pose a difficult ethical dilemma that should be addressed based on societal and ethical frameworks. Issues such as water allocation and pricing, privatization of various water services, and efficient water management need to be contested within an ethical framework according to principles of equity and social justice. This paper presents the basic concepts of water ethics, as well as water ethics perspectives and applications within the framework of integrated water resources management (IWRM) in the Arab Region, which suffers from one of the fastest growing water deficits in the world. The deteriorating status of the water resources situation in the Arab Region is no longer tolerable due to the high costs in terms of negative environmental consequences and deteriorating livelihoods of poor populations associated with lack of access to clean water and sanitation. Nevertheless, most of the national efforts for IWRM implementation in the Region have been dominated by neo-liberal economic policies stressing privatization of various water services; cost recovery through different pricing and tariffication schemes; as well as sectoral water (re)allocation. However, many negative impacts due to the shift to neo-liberal market-led economies have surfaced throughout the developing world in the past decade and a half, especially with respect to the increased levels of poverty and worsening environmental degradation. It is, therefore, critical to adopt IWRM approaches in the Region within an ethical framework that takes full consideration of all social implications regarding the poor, and that could be used as a means to achieve water-related international goals of poverty reduction. Finally, the paper also shows that there is no contradiction between Islamic beliefs, which constitute the chief cultural and ethical source of most Arab societies, and worldwide accepted IWRM principles and associated ethical frameworks.

Keywords: Water ethics, integrated water resources management, Arab Region, water ethics in Islam

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I. Introduction

Water ethics, as a specific and distinct philosophical field, is emerging in academic arenas, professional discussions, and dialogues on water governance. Concerns of water conservation, as well as adequate access to basic needs of water and sanitation and the deprivation of poor and marginalized communities throughout the world of such a fundamental human right, mostly due to the lack of empowerment and the inability to pay for the service, pose a difficult ethical dilemma that needs to be solved based on societal and ethical frameworks. These frameworks are also necessary to address issues such as the allocation of limited water resources and its relationship to efficiency, productivity, valuation, as well as principles of equity and social justice. Such ethical perspectives are especially significant for consideration of environmental conservation and sustainability for future generations within the contexts of integrated water resources management.

The philosophical side of this paper focuses on the basic concepts of environmental and water ethics and their relationship to human normative behaviour. The practical and institutional side of the paper, on the other hand, deals largely with environmental and water management laws and policies in the Arab Region. Most countries in the Region now have laws and policies relating to the environment to assess and mitigate the impacts of development and to control the contamination and depletion of their natural resources. These laws and policies should be scrutinized from ethical perspectives to ensure that their social impacts do not contradict with the goals of poverty alleviation in the Region.

Ethics and Normative Behaviour

Ethics is a branch of philosophy that looks into morality. Accordingly, "[ethics] looks at the meaning, therefore, of statements about the rightness or wrongness of actions; at motives; at blame; and fundamentally at the notion of good or bad" (Katz, 1991). Nevertheless, ethics is not only the result of existing human or cultural values. Much of environmental ethics, for example, stem from other types of knowledge, such as ecology, which has driven many of us to think morally about our uses and abuses of the environment, and the impact that societies and modern forms of development has had on natural resources.

Normative behaviour implies the involvement of values, or the foundations of moral principles, adopted or accepted by a particular society. By definition, values are "the moral principles and beliefs or accepted standards of a person or social group, so that they are likely to be culturally relative" (Katz, 1991). This means that values are likely to be culture-specific, and thus they tend to be relative. However, moral principles are usually used to assess actions as morally 'right' or 'wrong' and hence subject them to an absolute standard rather than any culturally acceptable way of doing things. This idea is extended towards the values that humans may or may not hold regarding the environment, the use of its natural resources, and the impacts of human activity on it. At the root of laws and policies (standard manifestations of human normative behaviour) that intend to protect and preserve the environment from human activity impacts and lay a set of moral principles and beliefs that are accepted by different societies (Simmons, 1993).

Water: the Crucial Natural Resource

Throughout history water has always been looked at as a special natural resource which is essential for the existence of life and human civilization. Fierce competition has always existed among various species as they strive to secure their basic water needs and ensure their survival. Historically, one can trace the development of human societies in areas where freshwater is available and accessible. As the size of the human population is increasing and the standard of living improving, water use per capita has been increasing at twice the rate (Hinrichsen, 2003).

Livelihoods of poor populations are directly linked to secure an equitable access to clean water and rational management of water resources. Providing safe water and good sanitation is fundamental to people's health and welfare. However, finding sustainable solutions to produce more food with less water, whilst safe-guarding the environment is equally important. Provision of adequate quantities of clean water, and related sanitation services, both for domestic uses and food production allows poor people to expand their income earning opportunities, protect their health, and reduce their vulnerability to natural disasters.

Water Ethics: Global Perspectives

Global ethical perspectives of water resources management are based on the recognition of the complex interdependence between sustainable development and increasing poor people's access to water and sanitation services in order to alleviate poverty, sustain livelihoods of poor populations, and safeguard the environment. The importance of water for poverty reduction and achieving sustainable and equitable development was recognized in the Millennium Development Goals (MDGs). The Millennium Declaration sets the target of halving the number of people who are unable to reach, or afford, safe drinking water by 2015 (MDG No. 7). It also calls for discontinuing unsustainable management of water resources through the development of IWRM strategies at the regional and national levels. The significance of meeting global water challenges was reaffirmed at the World Summit for Sustainable Development (WSSD) in Johannesburg in 2002. The Johannesburg Plan of Implementation of the MDGs spells out concrete actions and targets to increase access to water and sanitation, and to put in place national IWRM plans.

Developing a comprehensive ethical framework that would set the base for equitable practices to mitigate global water-related poverty challenges became a necessity with the above-mentioned international efforts for efficient water management. This necessity was acted upon by United Nations Educational, Scientific and Cultural Organization (UNESCO) through the creation of the World Commission on the Ethics of Scientific Knowledge and Technology (COMEST) in 1997. To achieve its goals COMEST established four sub-commissions, one of which was the Sub-Commission on Freshwater Use which focused on water ethics (Brelet, 2004). In addition, the International Hydrological Programme (IHP) at UNESCO created an intercultural and interdisciplinary working group on ethics of freshwater that published a report entitled "Ethics of the Uses of Freshwater" (Rahaman and Varis, 2003). Moreover, COMEST established, with the IHP/UNESCO, the Research and Ethical Network Embracing

Water (RENEW) with a mission to 'promote engagement in the ethical issues involved in the sustainable use and equitable sharing of freshwater resources' (Brelet, 2004).

II. Principles of Water Ethics

The work and publications of the Sub-Commission and the Network culminated in a framework for water ethics based on the following basic ethical principles: human rights and dignity, equality, solidarity, stewardship, transparency, participation, inclusiveness, empowerment, and defining water as a common good. This framework views water as an exploitable good, from which all individuals within society have the right to use their basic needs for life. The framework also calls for keeping the integrity of water resources, as well as the respect to the values (or systems of beliefs) adopted by different societies including indigenous and marginalized ones. Following is an analytical description of the above principles that shows the inter-relationship between them all.

Human Rights and Dignity

Today more than one billion people throughout the developing world lack access to safe drinking water and three billion lack access to adequate sanitation. This failure, incurred by the international development assistance community, led to substantial human suffering which has been reflected in loss of dignified livelihoods as well as mass movement and forced displacement of poor populations seeking water. Considering water as a basic human right is extremely important since it encourages the international community, as well as national governments, to work hard towards the target of universal access to clean water. Moreover, acknowledging this right creates the necessary ethical pressure to implement it within national and international agreements and conventions (Gleik, 1999).

It should be noted that in international legislation, universal right to water was only expressed in the Convention of the Rights of the Child (Gleik, 1999). Additionally, in 2002 the United Nations Committee on Economic, Cultural, and Social Rights issued a "General Comment" which openly expressed that the concept of water management is not to be limited to its economic dimension only, and that access to water should be considered as a human right. The Comment clearly states that everyone is entitled to sufficient, affordable, accessible, safe and acceptable water for personal and domestic usage (UNESCO, 2003).

Equality

The principle of human equality stresses that all individuals within society should be provided with their basic needs on an equitable basis through universal access to clean water and sanitation (Brelet, 2004). Considering the concept of human equality is, therefore, very important at the policy development level when allocating water among competing sectors and interests in society. It is firmly established and accepted that first priority in sectoral water allocation must be given to basic human needs (Rahaman and Varis, 2003). However, income-generation and economic efficiency considerations also influence water allocation due to their important effect on socio-economic development and poverty alleviation efforts. Nevertheless, it is equally important to consider water requirements for sustainable livelihoods of the poor populations, not only economic efficiency, in order to achieve overall societal development (Vasiliev, 1998).

Appropriate prioritization is especially significant in arid and semi-arid regions, such as the Arab Region, with limited water availability. Among major conflicts with ethical ramifications in such regions, is allocating water for irrigation. Given that food is also a basic human need it is only ethical to provide water for agriculture in the interest of supporting human life through the production of food. However, in many cases supporting agriculture takes the form of subsidizing water for irrigation and encouraging farmers to plant high-value cash crops that require large amounts of water and deprive other sectors, including the maintenance of ecological integrity, from their necessary water needs (Rahnema, 2002). Therefore, it is ethically required to look into environmental and socio-economic consequences and consider the use of water pricing incentives for water conservation when allocating water for irrigation. As a matter of fact, allocating water to support the ecosystem is an ethical dilemma in itself. The inter-generational dimension of human equality constitutes a firm ethical basis for recognizing in-stream uses and ecological and environmental conservation in water allocation policies.

Solidarity

Solidarity among various water users is an essential prerequisite for universal and equitable provision of basic needs of water for all. Water use and management, especially in drylands, are always fraught with conflicts arising from water scarcity and non-uniform distribution both spatially and temporally. These conflicts are mainly manifested through intra- and inter-sectoral water allocation problems, as well as issues of upstream-downstream interdependence. Water sharing in cases of scarcity is among the earliest subjects of conflict between water users on the international and national levels, especially when priority in water allocation is given to the agricultural sector over other sectors (Rahaman and Varis, 2003).

Stewardship

Stewardship towards water resources and the environment is closely inter-related to principles of human rights, equality, and solidarity. Wise use and conservation of water quantity and quality, as well as respecting the environment and securing its basic requirements for ecosystem maintenance, are fundamental for the application of water ethics principles. A major decision is how much water should be allocated for current human use (for agricultural, industrial, and domestic purposes) and how much should be used to maintain ecosystems and conserve the environment for future generations (Rahaman and Varis, 2003). This problem is further magnified in arid and semi-arid regions. It is therefore necessary to quantify the costs and benefits to society that stem from allocating water for ecosystem maintenance. This process requires accurate information and data on water demands of various sectors and human needs and the value of ecosystems and natural resources for current and future generations (Selbourne, 2000).

Defining Water as a Common Good

Water resources occur naturally and provide an open access for all. Thus water is considered as a common good, especially that it is an essential requirement for life. A common good is defined by three characteristics: (1) non-rivalrous: one person cannot deprive others from using it; (2) non-excludable: impossible to restrict others from using it; and (3) non-rejectable: individuals cannot abstain from its consumption even if they decide to (Bannock et al, 1987). However, according to Hardin (1968), over-exploitation of common goods occurs due to the phenomenon called the "tragedy of the commons" where users ignore the impacts of using the resource on its current and future availability for other uses and users.

Economists' prescription to solve the "tragedy of the commons" and conserve the resources is to clearly define private water rights and establish water markets. In fact, both Agenda 21 and the Dublin Principles (WMO, 1992) positioned the argument of treating water as an *"economic good"* highly on the global agenda. This argument has received worldwide acceptance, as it came out at a time when neo-liberal ideas started to have a very strong influence on international development and policy debates, especially regarding water management. However, according to Rogers et al (1998), this has created confusion because water is not a typical private economic good since it is essential for human life, and water and sanitation are regarded as services that people have a right to regardless of whether they are able to pay for them or not. Therefore, the only complete and viable solution to the "tragedy of the commons" can be achieved by full recognition of equality, solidarity, and concepts of human rights by decision makers, managers, and users.

Participation, Empowerment, Inclusiveness, and Transparency

The importance of *participation* does not only lie in being among the principles of ethical water management or good water governance. Experience shows that with an open social structure, which enables broader participation by civil society, water governance is more effective because of the civil society's ability to influence government. Therefore, citizens should be able to have a say, directly or through civil society organizations, in relevant decision making and policy formulation processes (UNDP, 2003). Government regulations that facilitate local participation in water management are necessary for a clearer and more effective role of non-governmental organizations and civil society in general (Rogers and Hall, 2003).

Therefore, *empowerment* of local communities, especially remote and marginalized ones, through creating an enabling environment for more effective action of the civil society is an important prerequisite to achieving a meaningful participation in water resources management. Moreover, the effectiveness of government policies depend on ensuring participation throughout the policy formulation and decision making processes. This would create more confidence in the developed policies and the institutions through which such policies are formulated.

On the other hand, participation crucially depends on all levels of government following an inclusive approach when developing and implementing water policies. *Inclusiveness* can be achieved through social mobilization and freedom of association and speech. As such, institutions should communicate with all stakeholders involved in the issues of water resources management. This entails conducting accurate and well-informed stakeholder analyses at all levels of decision-making, whether at the policy level (as mentioned above) or at the local level that requires the inclusion, empowerment, and participation of local people.

Finally, water management should be done in an open manner with full *transparency.* All decision making and policy formulation processes should be transparent so that all involved stakeholders could follow the details of developed policies. For that, various roles in the legislative and executive branches of government need to be clear, and decision-makers, private sector, and civil society organizations should be accountable to the public. Accordingly, the consequences of any violation of policy provisions should be clear among stakeholders (Rogers and Hall, 2003).

III. Water Ethics and Rational Water Governance

Rational Water Governance

Water governance refers to the range of political, administrative, economic, and social systems that are put in place to develop and manage water resources and the delivery of water services (UNDP, 2003). The general principles of rational and effective water governance are basically equity and efficiency in allocation of water resources and access to clean water and sanitation; balance between social, economic, and environmental water utilization and maintenance of ecosystem integrity; holistic and integrated management approaches; as well as full community participation in the management of local water resources. These principles, which obviously coincide with the water ethics principles discussed in the previous section, are addressed through IWRM approaches that are characterized by transparency of decision-making, as well as accountability and responsiveness to society's value system(s). Therefore, rational water governance and its IWRM tools are the main mechanisms through which a society's water ethics framework is implemented.

Integrated Water Resources Management

The concept of IWRM has been coined and advocated by the international community since the early 1990s, and it gained wide acceptance as an appropriate management tool for rational water governance. IWRM is an ecosystem-based approach that takes into consideration the inter-relationships between natural resources systems and socio-economic objectives, and attempts to integrate them with national development and poverty alleviation objectives. It should be noted that the IWRM approach can be implemented only within a society-adopted ethical framework. All management tools of IWRM should be based on established ethical principles for water resources management in order to be adopted by society. Otherwise some of these tools, especially economic instruments, might reduce access to clean water and sanitation among poor and marginalized groups of population.

The integrated nature of the IWRM approach ensures equitable access to water for all population sectors while taking full consideration of economic efficiency and environmental integrity. In other words, the individual human right of access to basic needs of water is ensured while the interests of the society as a whole in economic development and preserved environment are fully considered. Therefore, the concept of solidarity among various water users, with varied geographical and inter/intra-sectoral interests, is inherently embedded in the approach. Moreover, examples where IWRM has been a useful tool in solving international and trans-boundary water conflicts suffice to show the importance of solidarity between different parties in solving such conflicts (UNDP, 2003).

IV. Water Ethics Perspectives in the Arab Region

The Arab Region is experiencing one of the fastest growing water deficits in the world. The majority of the Region's countries have been consuming more water than their renewable supply for quite some time. However, this is no longer an option due to its high costs and negative environmental consequences that have been leading to a vicious cycle linking deteriorating status of water resources, in terms of quantity and quality, to deteriorating livelihoods. General lack of familiarity with participatory and integrated management approaches; fragmented institutional structures and conflicting mandates; outdated water pricing policies; imbalanced sectoral water allocation; persistence on solving increasing demand problems through expensive supply augmentation; and delegation of responsibility without the necessary devolution of power and financial resources in decentralization plans are among the major problems facing water management throughout the Region.

Water scarcity and uneven geographical and seasonal distribution, mismanagement and ineffective water governance, deficiencies in access to clean water and sanitation services in remote areas, as well as pollution and degradation of aquatic ecosystems have in most cases had severely limiting effects on development options for poor communities and other marginalized groups in the Region. Moreover, inadequate investment in societal, institutional, and human capacity development has worsened the situation. It is therefore critical to expedite the adoption of integrated water resources management approaches, within a societal ethical framework for water management, in order to enhance effective water governance and achieve poverty alleviation goals in the Arab Region.

Ethical Framework for IWRM Implementation in the Arab Region

With the issues of water scarcity and mismanagement coming up, countries in the Arab Region are faced with the pressing need to initiate cooperation among each other through regional programmes and develop their own national plans for the adoption of IWRM approaches. As a matter of fact, some countries in the Region have already started to establish the necessary institutions and develop national plans for IWRM implementation. It should be noted, however, that most of the national efforts in the Region for IWRM implementation have been dominated by neo-liberal economic policies that are globally gaining ground since the early 1990s as the main vehicles for growth and poverty reduction.

These country efforts, which significantly benefit from bilateral assistance programs with various donors and active international agencies in the Region, mainly rely on neo-liberal free market tools and mechanisms. Interventions in the water resources sector mostly constitute of *decentralization* schemes for local water resources and watershed management; *privatization* of water supply and other related services; development of *water pricing* schemes that ensure service cost recovery; *sectoral water (re)allocation*; expansion of *access to water and sanitation*; as well as *water quality management*. The main rationale behind the heavy reliance on such tools is that using free market principles and treating water as an economic good enhances water use efficiency; helps balancing the budgets of water supply authorities; leads to better conservation of water resources; and eventually helps improve the access of poor and marginalized communities to water and sanitation.

However, many negative impacts of market-led economies have surfaced throughout developing countries in the past decade and a half. The most significant of these impacts, faced in certain cases, have been increasing poverty levels among most severely disadvantaged sectors of society, as well as environmental pollution and degradation when rules of free market economy are left alone in control (Woodhouse, 2001). Promoting the change to across-the-board free-market water pricing systems, for example, has always proved to be politically difficult due to the insensitivity of such systems to the weak ability of poor populations to pay for their access to basic water needs. This is specifically true in places where water has been historically heavily subsidized, as the case has been for a long time in the Arab Region. Therefore, the introduction of IWRM approaches should be done in such a way that earlier-acknowledged governmental responsibility to provide adequate water services for poorer sectors of Arab societies is not abandoned. On the contrary, adoption of the IWRM approach should be used as a means to achieve water-related international goals of poverty reduction.

IWRM Tools Used in the Arab Region

Below is an analytical description of the main pillars that have been recently used in the Arab Region for IWRM implementation, along with some general guidelines for implementing such tools within an ethical framework for water management adopted by societies in the Region.

Decentralization

Theoretically, decentralization should improve efficiency, accountability, and equity in natural resources allocation because it can more closely connect the benefits of local public services to the costs entailed. This is based on the belief that local governments are more knowledgeable regarding their communities' needs than the national governments. Moreover, decentralization has been seen as an effective tool in promoting good governance and democracy because it is easier to hold local governments accountable (to the local constituencies and national governments alike), and it can be successful in making the "state closer to the people" by increasing the participation of local communities (World Bank, 1997; 2000). In water resources management, decentralization allows for a wider margin of cost recovery of water and sanitation provision, efficient allocation of water to various economic sectors, as well as providing the necessary institutional enabling environment that is needed for proper accountability and control over services.

Nevertheless, decentralization has to be implemented appropriately and as open and transparent as possible in order to be considered ethical, because it has its obvious shortcomings and disadvantages. These include the possibility of the occurrence of *elite capture* that promotes clientelism instead of democratic participation. Local authorities might be heterogeneous entities pursuing a range of interests that could be in conflict with one another. More often in developing countries, including the Arab Region, the leadership of local authorities falls into the hands of the wealthy and powerful. The interests of the poor would not be of immediate concern to these authorities in such situations (Engberg-Pederson and Webster, 2002).

Moreover, there may be some problems facing water conservation in certain situations especially where the benefits may be national but the costs borne only on the local level. Central governments should provide, in such cases, innovative incentive structures containing a broader vision for local benefits of water conservation. This would equip local governments and the people at large with necessary incentives to conserve water, apply ethical principles of water management to local water projects, and enforce regulations that would protect their water resources from pollution (Lutz and Caldecoff, 1996; Larson, 2002). Therefore, decentralization is needed in water governance, but it should be balanced with an active central government role in order to achieve sustainable water management that would adhere to water ethics principles (Rogers and Hall, 2003).

In the Arab Region, different decentralization schemes for irrigation and domestic water supply have been adopted in various countries. Each experience has led to different impacts, but in general decentralization has raised to a certain extent the sense of responsibility among farmers and resulted in achieving higher water use efficiencies (Attia, 2003; ESCWA, 1999). However, while some countries in the Arab Region, such as Tunisia and Egypt, have already successfully implemented decentralization schemes, some other countries are still in the beginning stages of creating such an environment. In Lebanon, for example, the Ministry of Energy and Water has just started to plan a decentralization scheme for water resources management on the national level.

Other countries in the Arab Region, on the other hand, followed a more centralized approach, such as Algeria where the government created the Algérienne Des Eaux (ADE) agency for central planning and execution of all water management operations and the implementation of national water policies. Finally, it should be noted that it is still too early to evaluate the overall impacts of decentralizing water management in the Arab Region because the whole idea is relatively very recent in the Region. Even in the countries that have had a good start with the process, it is still premature to claim that they already enjoy a good enabling environment based on a societal ethical framework for water management.

Privatization

Policy makers in the Arab Region have chosen privatization as a strategic decision that involves major reforms in line with overall structural adjustment programmes aiming to reduce budget deficits and meet the increasing demand for water and sanitation services. Privatization contracts are being implemented in Gaza, Jordan, Lebanon, Qatar, and Yemen; while privatization agreements are being seriously considered in Bahrain, Egypt, Kuwait and Saudi Arabia. However, the Region still suffers from many problems related to water management privatization. Knowledge and information regarding the chosen privatization scheme(s) and their expected results have not been made available for societies throughout the Region in order to avoid any marginalization or distrust among the public.

Moreover, while in some countries of the Region there is strong political will and acceptable public adaptation to implementing water privatization other countries are facing severe resistance to this process. Opponents to privatization are accusing the governments of using non-transparent processes to sell off public assets cheaply and put responsibility for a vital scarce resource in private sector hands (ESCWA, 2003). Countries opting for privatization of water service delivery in the Arab Region should stress transparency and effectiveness and recognize social and ethical considerations while setting up the needed institutional structures and developing the necessary legal and regulatory frameworks that would ensure transparency and justice of privatization schemes.

In general, private sector participation has been widely promoted in water resources management as part of neo-liberal reforms that have been driven by multilateral and international financial institutions and adopted by most bilateral development agencies. Despite local community and civil society resistance to various attempts at privatizing water resources, privatization is viewed by many in the international development arena as the best means for enhancing operational efficiency in water services and increasing financial resources that would help expanding access to water and sanitation. The rationale behind this position is that experience with using public utilities for water service provision has shown that such institutions suffer from the inherent public sector inefficiency and corruption and that in general they are too slow in adapting to increasing demands.

However, increasing private sector involvement in water resources management remains controversial. While many believe that engaging the private sector would accrue enormous benefits to society, others believe that the process of providing water and sanitation services is strictly a matter of public governance (Bennett, 1998). For example, private water companies would not be eager to invest in water utilities unless they are profitable. Consequently, affluent urban neighbourhoods would get the lion's share of investments, which are usually already better served compared to peripheral rural areas, due to their greater ability to pay for their services. Moreover, increased productivity through privatizing water resources management usually involves major "labour shedding" which, in turn, entails social problems (Budds and McGranahan, 2003; Rees, 1998). Consequently, major ethical questions should be asked regarding the deteriorating livelihoods of the concerned labour force families, as well as those of urban and rural low income communities left out of service, versus society's gains in efficiency and productivity.

Therefore, what can be said about private sector participation in water management is that it is not a magic solution. Questions should also be asked, when decisions are taken about privatization of water services, regarding *considering water as a common good or as an economic good* with all the social and ethical ramifications of such decisions. In some cases, when people in poor neighbourhoods are not able to pay for water and sanitation services, difficult decisions have to be made. Such cases can be addressed only through public regulation based on ethical principles that consider water as a basic human right for all. From an ethical perspective, water can be optimally managed when it is considered as a common good which possesses an "economic value" that must be collected from users in order to ensure conservation and prevent wastage. Even with privatized management, to achieve the required level of access to water and sanitation a combination of regulation, targeted subsidies, and obligatory service fees is needed to bring about the desired goals and benefits (Budds and McGranahan, 2003; Guiterrez, 2001).

Water Pricing

As mentioned earlier, well known is the overall economists' preference for defining private water rights and creation of water markets through viable water pricing mechanisms in order to solve the problems of over use (Johansson et al, 2002). Building on the assumption that humans are rational consumers, if service costs are covered by the State and hence no water pricing mechanisms exist, there will not be any incentive to conserve water and use it rationally (Abu-Zeid, 2001; Dinar and Subramanian, 1997). On the other hand, it is believed that long term sustainability of water supply services is achieved only by fully recovering all the incurred costs of infrastructure, operation, maintenance, administration, and development of the needed facilities (Budds and McGranahan, 2003). Consequently, proponents of cost-recovery water pricing mechanisms claim that efficiency gains from such mechanisms benefit all service users, including the poor sectors of society who would gain by becoming connected to a reliable and sustainable system.

Yet, the notion of an optimal water-price does not command consensus among economists and policymakers, as there is still disagreement regarding the derivation of the "right" water price. Because water is vital for life, and it is considered as a basic human right for all, its value should not be defined in economic terms only but should also reflect the social, environmental, cultural, and religious morals placed on it. The commodification of water in general is fraught with social and ethical problems since water pricing mechanisms based on full cost recovery and total removal of subsidies mostly lead to unfair distribution of service costs. Ethical concerns of "human equality" and "solidarity" across economically disparate groups in a society could necessitate the implementation of differing pricing mechanisms for the sake of sustaining livelihoods and expanding access of the poor to water services (Dinar and Subrumanian, 1997). Affluent sectors would in effect subsidize the water supply for poor sectors of the society. However, it is important not to totally sacrifice water demand management considerations, for the sake of equitable access, in order to induce water conservation among all users (Linam, 2002).

According to ESCWA (2003), water-pricing schemes currently used in some Arab countries are not leading to water conservation and improved water use efficiency. Setting water prices at lower than production costs is still common in most of these countries. This is especially flagrant in the irrigation sector, where water is still highly subsidized in several Arab countries in spite of the widespread water over-consumption in this sector throughout the Region (Abdurazzak and Kobeissi, 2002). It should be mentioned, however, that some Arab countries are already implementing efficient water pricing schemes, which take ethical issues of societal solidarity and equitable access to water into consideration. In Jordan, for example, a water pricing scheme has been implemented using the concept of the "lifeline rate schedule." The scheme is designed to recover the service costs while keeping "lifeline" basic needs affordable for the poor (Taha and Bataineh, 2002). Also, in Tunisia a progressive block rate and selective pricing of drinking water has proved to be efficient in cost recovery, as well as a means for enhancing equitable water use. Nevertheless, this system has not been without limitations in terms of over use of water. Bringing pressure to bear on major consumers only, left small and average consumers, who are spared to a great extent by paying a heavily subsidised price, with very little incentives to conserve water.

Sectoral Water Allocation

Water resources problems in most Arab countries can be attributed not only to natural limitation in water availability, but also to rising demands and unsustainable practices of overuse in various sectors, diminishing resources owing to increased population, lack of sustainable water policies, as well as the lack of the adequate financial resources for water resources development. According to ACSAD (1999), agricultural water sector requirements account for most of the water used in Arab Region. In fact, the agricultural sector is by far the largest user accounting for around 85% of total use in the Region compared to around 60% worldwide water use for agriculture (Berkoff, 1994). Moreover, not only countries blessed with large river flows in the Region, such as Egypt, Iraq, and Syria allocate most of their water supply for the agricultural sector, but also countries like Jordan, Kuwait, and Yemen which suffer from severe shortages still over allocate water for agriculture. The problem is even worsened by the phenomenally low irrigation efficiency prevalent in the Region where average water requirement per hectare is estimated at 11,500 m^3. On the other hand, agricultural sector contribution to the gross domestic products (GDP) of various countries in the Region is relatively small. Moreover, the goal of self-sufficiency in food production and food security, which is the stated reason behind sticking to the flagrant imbalance in sectoral water allocation throughout the Arab Region, is proving economically and physically unrealistic day by day.

Therefore, appropriate prioritization of water allocation to various user sectors can be considered among the major ethical challenges in water management throughout the Arab Region. Unless serious efforts are made to increase water use efficiency in irrigation, reuse of treated wastewater, and cultivation of crops that do not require large amounts of water, it is expected that the agricultural sector would continue to consume water amounts beyond the available capacity. This water overuse would threaten other economic sectors (due to diminishing availability) and eventually subject the health and welfare of people in the Region to serious risks (ESCWA, 2003). Accordingly, decreasing water use in agriculture, and reallocation of some conserved resources to other sectors (especially domestic), is necessary to ensure the availability of basic water needs for maintenance of public health and economic development in most of the Region's countries.

For some countries in the Arab Region, however, the agricultural sector presents the main economic backbone for food production, and the main driver for sustaining livelihoods through employment. This is extremely important in countries like Egypt, Iraq, and Syria where subsistence farming is among the largest economic sectors. In such countries, utmost consideration should be taken with respect to sustaining livelihoods of subsistence farming communities when sectoral water reallocation is considered. Encouraging subsistence farming which is not an intensive water consumer, rather than large-scale industrialized farming systems, would significantly reduce the threat to both water availability and pollution without threatening the livelihoods of farmers and the economy of rural areas in the Arab Region. In fact, increasing irrigation efficiency, while sustaining the livelihoods of families that are dependent on subsistence farming systems, is among the major challenges facing the IWRM implementation throughout the Arab Region (Herromoes, 2001; Rahaman and Varis, 2003).

Access to Water and Sanitation

The main issues of concern under water and sanitation are *access to safe drinking water and sanitation* services, as well as *water quality management*. Development of water and sanitation infrastructure and facilities, and provision of equitable and universal access to such services, is considered as a basic human need (and right) and a cornerstone for economic and social development. In the Arab Region, access to safe drinking water is approaching 100 percent of the urban population (Berkoff, 1994; UNICEF, 1998). However, only 60 percent coverage has been reached in rural areas of the Region, which is well below the developing countries' average that was raised from 71 percent in 1990 to 78 percent in 2000.

This gap between the urban and rural areas' services is reflected, as well, in some health indicators such as the infant mortality rate (IMR) in the Region. Despite the decreasing IMR levels in the Region as a whole, as a result of growing water and sanitation services (Berkoff, 1994), according to the Arab Human Development Report (UNDP, 2002) great disparities in the IMR figures still exist between rural and urban areas. The ratio of rural to urban under-five mortality in the Region ranges from 1.21 to as high as two-fold. Even countries with high levels of water/sanitation services that succeeded in lowering the general under-five mortality rate still suffer from this difference, which poses a serious challenge in terms of equality of services for urban versus rural areas.

Measuring the quality of water/sanitation service provision includes both the quantity and quality of water, with the latter being especially important for domestic supply. An alarming indicator for poor water quality management in the Arab Region is the big difference between the access to safe drinking water and access to sanitation services in several countries of the Region. There is a pressing need for a policy shift in the Region toward continued expansion of water supply and sanitation coverage in rural areas linked to upgraded service level that ensures acceptable water quality coupled with enhancing water quality management at the household level (UNESCO, 2003). Evidently, more investment is needed throughout the Arab Region's rural areas in order to meet the international goals of water and sanitation coverage, such as the MDGs.

A major ethical challenge, therefore, throughout the Arab Region is to ensure that enough investments are made in water and sanitation infrastructure in poor and rural areas. It should be noticed that, because private water companies are usually uninterested in providing water services for poor and marginalized regions like remote rural areas due to their main interest in cost recovery issues, water sector interventions in such areas are usually mostly implemented by government agencies or nongovernmental organizations (NGOs) (Budds and McGranahan, 2003). Starting with the felt needs and existing capacity of poor communities, these interventions should allow expansion and upgrading toward internationally accepted standards of water and sanitation services (UNICEF, 1998). Whether government led or privatized, services should be operated and maintained with full participation by all stakeholders. Equality, especially gender equality, is a central issue in all aspects of increasing the access of poor people to good-quality water and sanitation services (Soussan, 2004).

V. Water Ethics in Islam

Water is given great importance in Islam, and it is considered as a blessing from God that sustains life. In addition, ensuring social justice for Muslims is among the cornerstones of the Religion. Most of the Prophet's "hadith" is about the preservation of justice and equality including equality in water use and access to water resources for all sectors of society. Consequently, true Muslim believers cannot grab water in excess to their needs since they are obliged to allow free access to any amounts of water beyond these needs (Faruqui, 2001; Naff and Dellapenna, 2002).

Islamic thought is the chief cultural and ethical source of predominantly Muslim Arab societies. Consequently, any ethical framework for water management in the Arab Region has to be in agreement with Islamic beliefs and condoned by relevant Islamic rules. Therefore, looking into Islamic ethical bases for integrated water resources management is a necessary prerequisite step for developing such a framework. Actually, extensive Islamic rulings cover a wide range of issues in *environmental and water management from environmental stewardship and water conservation* to *sectoral allocation, water pricing,* and *privatization* in the water sector. Below is an analytical description of these rulings, which are all based on Islamic values that call for social justice and participation of all sectors of society in the management of its common natural resources.

Environmental Stewardship and Water Conservation

According to Islam, humans are the most favoured of God's creatures. However, they are responsible for ensuring that nature, God's gift to humanity, is well conserved and taken care of so that it would be equitably available for all on planet Earth. Therefore, the environment must be protected by humans with clear command against upsetting the natural order through pollution or over exploitation. Accordingly, in the Quran, God commands the believers to *"make not mischief on earth,"* i.e. they should not degrade or pollute natural resources. Water conservation in quantity and quality is specifically encouraged within Islamic laws. The Quran tells the believers that they may use God's gifts, such as water, for their basic needs for survival, provided that they do use it in moderation not in excess (Faruqui, 2001).

Among mostly used water conservation tools is the reuse of treated wastewater for irrigation. Treating and reusing wastewater, especially domestic sewage, has many advantages in water management, since they allow the conservation of freshwater for the highest-value uses. Moreover, the reuse of nutrient rich wastewater helps control the environmental impacts of dumping raw sewage in streams and water bodies and enhances agricultural productivity. However, with the utmost importance given to personal cleanliness and public hygiene in Islamic tradition, most Arab societies have been sceptical in their initial response to the idea of wastewater reuse for irrigation. But several "fatwas" have been issued after consulting with scientists and engineers, such as the "fatwa" of the Council of Leading Islamic Scholars in Saudi Arabia for example, stating that treated wastewater can theoretically be used for all purposes as long as it does not pose any health risk to society (Abderrahman, 2000). As a result, treated wastewater reuse for irrigation in GCC countries including Saudi Arabia have been practiced since 1978.

Water pricing

In Muslim nations, water pricing is a complicated and disputable since, as mentioned above, the Islamic perception is that water is a common public good which should neither be bought nor sold (Faruqui, 2001). However, according to Kadouri et al (2001), most contemporary Islamic scholars have concluded that, in spite of its original nature as a common good, individuals have the right to use, sell, and recover value-added costs of developed infrastructure for water supply services. Accordingly, water resources in Islam are categorized as follows:

- *Public property*, which is water in its original state as a natural resource with free access for all.
- *Restricted private property*, such as lakes and rivers, where owners may have certain rights, but also have obligations (e.g. should not hold back surplus water).
- *Private property*, which is developed through investment in infrastructure works.

Based on the discussion above, in principle it is not against Islamic ethical beliefs to charge a price for water supply. However, it is important to note that within Islam, such prices should be a "fair price" that would lead to greater equity in water use which should be the first consideration in any economic instrument used for water management. Thus water tariffs based on price elasticity of demand are allowed in Islam as they are equitable in principle. On the other hand, cost recovery is also allowed in Islam due to its positive effect on enhancing water conservation and water services for poor communities (Faruqui, 2001). Moreover, since Islam encourages environmental protection, the price can include the cost of wastewater collection and treatment.

Privatization

The goal of full cost recovery of water service delivery is best reached through the participation of private partner(s) with the public sector. Islam supports privatization of water supply and sanitation provision in principle as long as it leads to a fair and free market, which results in equitable cost sharing. After all, Prophet Muhammad was a businessman prior to his Prophecy, and he set an example for ethical business dealings. Muslim scholars agree that privatization is allowed within Islam as long as users are served equitably and charged a fair water price.

Sectoral allocation

According to Islam, and during the days of the Islamic state, water use was prioritized in order to make the most of available water quantities for the whole population. As such, irrigation was given third priority, behind domestic use and "quenching of thirst" which was assigned the first priority. Consequently, contemporary Islamic scholars consider reallocation of water among sectors and giving priority to basic water needs for life as a necessity that is not in conflict with Islamic belief. Moreover, reallocating water from the agricultural to the domestic sector enhances social justice and equality in water use which are very important in the Muslim faith. These are very important considerations in some countries of the Arab Region in which sectoral reallocation of water has become a dire need.

Participation

Contrary to the centralized governance and decision-making systems that exist in most Arab countries, community participation in all public matters such as the management of water resources is mandatory in Islam. In the Quran, believers are defined as those who would, among other things, manage "their affairs by mutual consultation." As such, according to Islam, this consultation is required of all those who are entitled to a voice including women. Therefore, all members of society should be proactive in developing and implementing proper participatory water management schemes. Furthermore, the role of each and every individual in society is important when it comes to spreading awareness for water use and conservation. It should be mentioned here that Muslim clerics have an important role to play with respect to preaching and educating people according to the aforementioned principles of ethical water use (Faruqui, 2001).

VI. Conclusions

As mentioned in earlier sections, efforts for IWRM implementation in the Arab Region have been heavily dominated by neo-liberal policies that are gaining grounds around the globe. Neo-liberal management tools such as decentralization of water resources management, privatization of water services, water pricing reforms aiming at full cost recovery, and sectoral water re-allocation leading to higher efficiency, are all being planned and/or implemented for the water sector in the Arab Region with the presumption that treating water as an economic good and using all these tools for managing water resources improves the overall efficiency in the sector and eventually leads to water conservation and expansion of access to water and sanitation in the Region. However, typical negative impacts of free market-based neo-liberal policies for water resources management, like initial reduction in access to water for poor populations due to their inability to pay for the services, and the consequent increase in poverty level, as well as environmental pollution and degradation, have been well known wherever these policies have been put to work.

Therefore, developing an ethical framework, based on universal human right to water and other global principles of water ethics, to guide the whole implementation process of the above mentioned management tools has become a necessary step for successful transformation toward IWRM adoption in the Arab Region. It is obvious from the previous section that this can be done within predominantly Muslim Arab societies since there is no contradiction between Islamic belief and worldwide accepted ethical standards of integrated water resources management principles which balance equity, efficiency, and sustainability across society. As a matter of fact, one can summarize the Islamic perspective of proper and ethical water management by a single principle, i.e. enhancing equity among water users and justice for all. Therefore, IWRM measures can be implemented in the Arab Region while fully recognizing and adhering to ethical principles of equity, solidarity, and stewardship and respecting the societies' heritage and cultural background.

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Water privatization learning from different case studies

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ABSTRACT

A wide variety of techniques in privatisation have been developed for the implementation of infrastructure projects availing the private sector resources to design, construct, finance and operate facilities. Therefore, it would be interesting to know how the privatisation movement has taken place in different countries around the world, particularly in the field of the water sector, through cases study which were visited by the authors. These case studies also help to understand as to how these countries tried to choose the privatisation option and the difficulties and problems faced during implementation. This study covers three countries namely, Argentina, Emirates and the Philippines. A discussion on these case studies has been made where a compilation of comparison of all these case studies has been represented diagrammatically to highlight the common factors in these countries and the uniqueness for each country. This study also would endeavour to serve to certain extent as guidance for a privatisation initiative in countries like Saudi Arabia.

Keywords: Privatisation, BOT, BOO, Concession contracts

LESSONS LEARNED FROM THE CASE STUDIES OF WATER SECTOR PRIVATISATION IN ARGENTINA, THE UAE AND THE PHILIPPINES

Development of infrastructure and its services are central to the development and well being of a country. Infrastructure development of a country refers to the necessity to construct, repair, refurbish, and modernize the infrastructure which is made of up of public utilities such as power plants, telecommunications, piped water supply, sanitation and sewerage facilities, arrangements for solid waste construction and disposal, gas pipe lines, roads, dams, canals, urban and inter-urban rail systems, ports, waterways, and airports. Privatisation is a strategic planning approach that can be a valuable instrument for economic reform and development of infrastructure; as such, it now dominates the political economies of many countries (Al Al-Shaikh, 2003). The trend towards privatisation has gathered momentum and expanded rapidly to every part of the world. The goals are to increase productivity, spur innovation and limit governmental involvement in industrial activities. A wide variety of techniques have been developed for the implementation of infrastructure projects availing the private sector resources to design, construct, finance and operate facilities (Auger, 1999). Case studies in Argentina, the Emirates and the Philippines bring out how these countries delved into the various situations that forced them to choose the privatisation option in the water sector and the difficulties and problems faced during implementation.

1.1 CASE STUDY IN ARGENTINA

1.1.1 Introduction

In the end of 1980s and beginning of the 1990s, Argentina's economy was failing and the macro-economic situation was very alarming; the annual inflation rate was 5,000%. To come out of the financial crisis, officials at the highest levels of the government and then-President Menem took the decision to obtain Congressional approval and passed two laws: the Economic Emergency Law of 1989, and the Public Sector Reform Law to begin a drastic change in national economic policy (Shaikh, 1996). These laws enabled the President to issue decrees, without congressional approval, for the privatisation of certain sectors.

This case study covers the privatisation of distribution and treatment of water, not the supply source. The need for privatisation of the supply source is not needed in this country, as the main source of water is from the live river La Plata which meets 90% of water supply, with the remaining 10% coming from renewable ground water.

The major players in the water privatisation of Argentina were:

1. OSN (Obras Sanitarias de La Naction), a public enterprise regulated by the government and is the water authority of Argentina
2. ETOSS (Ente Tripartto De Obrasy Servicios Sanitarios), a regulatory agency created by OSN after the award of the concession contract to oversee the concession contract
3. Aguas Argentinas, headed by Lyonnaise des Eaux-Dumez (France), the concession holder who took charge of the water distribution and treatment from the main activities of OSN.

1.1.2 Operational Activities of OSN

At the time of privatisation, OSN's Argentina's water authority had water facilities which included 77.5 kilometers of underground tunnels, 9 pumping stations, 2 treatment stations, 367 kilometer of water mains and more than 10,000 kilometer of distribution pipes. The sewerage system consisted of 4 pumping stations, 3 mains of 60 kilometers each, and about 7,000 kilometers of network pipelines. The system had only one sewerage treatment plant which was small and in poor condition, (Shaikh, 1996).

Average per capita consumption was very high – an estimated 300 to 500 liters per day. This figure reflected unaccounted system losses, which were estimated to be at least 40 percent of the total production of 100 million cubic meters of water per month in 1992. The rate charged in the Buenos Aires metropolitan area was US$ 0.40/m^3, which was high since the primary source of water is from the La Plata river which is free, fairly clean and located in the city itself (Shaikh, 1996). This cost covered all operating and maintenance expenses of pumping, treatment and distribution.

1.1.3 Privatisation of OSN

1.1.3.1 Privatisation Strategy Adopted

Given the need for large-scale investments, a concession arrangement appeared to be the most effective method for achieving privatisation objectives. It was decided not to break up the enterprise, but to grant a single concession covering all of OSN's existing operations, a strategy which helped to maintain the integrity of the system. A period of 30 years was determined to be suitable for the concession, since that time period was deemed sufficient to enable long-term investments to be financed and to allow the concessionaire a reasonable return on investments.

1.1.3.2 Preparation for Privatisation

A privatisation committee was established in early 1991, headed by an Undersecretary within the Ministry of Economy and Public Works, to oversee and coordinate the activities relating to the operation of the private concession.

Consultants were recruited through a competitive tender to help with the privatisation preparation for OSN and their fees were financed by the World Bank loan. There were two consultants, one technical and the other financial.

Consultants helped the government in drafting the regulatory framework, the bidding documents and the concession contract. The regulation system is very crucial and important to avoid the possible pitfalls associated with turning public monopolies into private ones (Shaikh, 1996).

1.1.4 Implementation

The concession was awarded through an international competitive tender. The bidding documents specified that no cash payment was required; instead, the concession would be granted on the basis of the greatest reduction offered in overall rate levels.

1.1.4.1 BID Proposal

The main elements of the bidding document were the bidder investment plan for the expansion and improvement of services. The concessionaire had to:

(a) Provide water to the users at the lowest rate and reduce unaccounted for water;

(b) Improve the quality of drinking water;

(c) Increase the water pressure; and

(d) Renovate all essential systems

The concessionaire was authorized to collect all customer payments and impose a penalty, including termination of service for non-payment of bills. However, the concessionaire was also required to reinstate service within 48 hours for customers who paid their bills and penalties (Shaikh, 1996).

Pre-qualification criteria were designed to limit the bidding to firms with strong technical and financial capability and to ensure that only top international operators could participate. In the tender evaluation of concession contract, a method of having a 'two-envelope' approach was used, one for the technical and other for financial.

In December 28, 1992, the Secretary of Public Works awarded the concession to the Aguas Argentinas consortium, headed by Lyonnaise des Eaux – Dumez, the award was signed in April 1993. The consortium began operation of the concession on May 1, 1993 (Shaikh, 1996).

1.1.4.2 Functioning of the Concessionaire

This contract is for serving the city of Buenos Aires and 17 metropolitan areas of nearly 10 million inhabitants. At the time of implementing this contract, 67% of the inhabitants had drinking water and 53% were connected to sewerage treatment networks operating with deficiencies. (Aguas Argentinas 1993-1999).

This organization was able to convince the labor unions to reduce the labor force by their offer of severance payments and related benefits, the employee stock ownership plan and the various training and retraining benefits. With the cooperation of unions, they reduced the work force through attrition and a voluntary retirement scheme and offered generous severance packages ranging form US$7,000 to US$ 10,000 per employee. The ratio of number of employees per 1,000 connections decreased from 8 to 3.5. Employees were entitled to a 10% share in the new company. (Shaikh, 1996).

1.1.5 Regulatory Body

After the award of the concession contract, a regulatory agency Ente Tripartto De Obrasy Servicios Sanitarios (ETOSS) was created. The main objectives of this body are:

1. To enforce the concession contract
2. To protect consumer rights
3. To supervise the maintenance and expansion of the system
4. To establish performance standards to ensure service quality
5. To guarantee the operation of current and future services and
6. To protect public health and water resources.

1.1.6 Outcome of Privatisation And Impacts

Good performance of the concessionaire, Aguas Argentinas is clearly seen from the Table No.1 below (web site information from Aguas Argentinas). (In Million $ pesos)

Table 1: Performance of Aguas Argentina

Year	1993	1994	1995	1996	1997	1998	1999(I)
Net turnover	150	292	360	390	412	460	544
Current net profit	(23)	25	53	58	57	53	92
Staff	7,865						3,864
Cumulated investments	127	272	544	786	1,038	1,195	1,395

(I) Audited figures ( ) Loss

1.1.7 Lessons Learned from Case Study

Much care had to be taken initially by the concession holder (the private sector serving this contract) when they lacked experience in operation and maintenance techniques; they also suffered a financial crisis when the country's fiscal situation was poor between 1989 and 1993.

Competitive auction of the contract produced a major price reduction and made it clear that the market was contestable. The Concessionaire has the incentives of higher inflow of cash when they cover more areas and the other incentive is from the reduction of wasteful consumption, since this reduces the amount it must invest in new production (Alcazar et al, 2000).

From examining this case of privatisation, it is clear that the regulatory agency should have been formed well before the start of the privatisation process, as the members of this agency were well experienced; most of them were from the private sector, and their expertise should have been utilized in drafting the concession contract document. This agency is solely responsible for monitoring the process on behalf of OSN and completely responsible for the success of the concession.

1.1.8 Conclusion

The water industry in Argentina began as a government monopoly. The concession method, which maintains the integrity of the system, was considered as most suitable, since there was no other competition. In the application of the concession, various enhancements, such as having more regulatory bodies, splitting of the system into different sub-sectors (production, transportation, distribution, etc.), different regions based on geographical and political factors, can ultimately improve service and create competition among players (Interview with Ing. Molinari).

From various literature reviews and from the discussions/interviews with various authorities (Molinari, Saltlel, Walton), we can say that it takes at least a year or two after major transactions are completed to reap the benefits of privatisation. The success and sustainability of privatisation in order to derive benefits for the people, government and the private sector depends on:

1. A stable government to build investor confidence in long-term projects such as the water industry
2. Setting up of regulatory body before the privatisation process and consumer representation in the regulatory body.
3. Clear and well defined laws and legal procedures, transparency and fairness in all dealings
4. Availability of accurate data on assets of public-owned water industry, age and condition of assets.
5. A correct formula to take care of exchange rate fluctuations to protect foreign investors
6. Stable tax structures
7. Effective regulatory body free from interference by politicians.
8. Tariff regulation mechanisms to protect consumer interest
9. Creating competitive atmosphere to avoid the danger of turning public monopolies into private monopolies by dividing the areas and systems for multiple players to reduced tariffs and better services.

10. Availability of all the required information to the investors who participate in the tender
11. Transparency of accounting system of the private sector
12. Acceptance and flexibility for cultural changes that may result due to the presence of multi-nationals.
13. Institutions to develop the managerial skills of authorities.
14. Effective and constructive role by the media.

1.2 CASE STUDY IN UAE

1.2.1 Introduction

During the period from 12th May to 13th May, 2001, we had very useful discussions and interviews with the authorities of Emirates Water and Electricity sector in United Arab Emirates (UAE).

The government of UAE realized that the government alone cannot sustain to supply the ever increasing demand for water and electricity as the revenue generated by the government will be siphoned off to this essential sector and may cripple their economy in the long run. Therefore, the government felt the need for a change in their policy to allow the private sector to participate in this field and thereby reduce their financial burden.

This case study covers the privatisation activity of water and electricity sector and how they implemented it in one of the new projects at Al Taweelah called the Taweelah A2 project.

1.2.2 Privatisation of WED

1.2.2.1 Privatisation Strategy Adopted

In 1996, the government of Abu Dhabi established a Privatisation Committee for the Water and Electricity Sector. The Committee was charged with examining the options for restructuring and privatizing the water and electricity sectors with the following objectives:

- Ensuring the security of water and electricity supply
- Improving economic efficiency and the level of service
- Promoting private sector investment and participation
- Creating employment and training opportunities for UAE nationals
- Maximizing revenues from asset sales (Annual Report-1999).

1.2.2.2 Preparation for Privatisation

The privatisation Committee's work resulted in the drafting and passing of Law No (2) of 1998 which enabled WED to restructure its functioning for achieving privatisation goals. The main provisions of the Law are:

- The creation of the Abu Dhabi Water and Electricity Authority (ADWEA). ADWEA is responsible for government policy towards the sector, including its privatisation.
- The transfer of control of WED to ADWEA.

- Planning and contracting for new production capacity was made the responsibility of a "Single Buyer", the Abu Dhabi Water and Electricity Company (ADWEC).
- The creation of an independent regulator for the sector, the Regulation and Supervision Bureau for the Water and Electricity Sector in the Emirate of Abu Dhabi (Annual Report-1999).

1.2.3 Implementation

1.2.3.1 BID Proposal

The Privatisation Committee issued in late 1997 a Request for Proposal (RFP) for a new generation and desalination station on the Taweelah site, known as Taweelah A2. This project was considered as top priority for issuing the RFP because of the urgent requirement of additional power and water as soon as possible. Also, the existing facilities like the seawater intake, site services, access and other facilities can be used and this will reduce site infrastructure development cost and save time for the project completion.

1.2.3.2 Contracting

The RFP was issued to eight pre-qualified international consortia. Bids from six were received in March 1998. Evaluation of bids was based primarily on price, calculated as the levelized average over the 20-year life of a Power and Water Purchase Agreement (PWPA).

Ownership and operation of the Taweelah A2 plant is to be the responsibility of the Emirates CMS Power Company, 60% owned by ADWEA through a holding company (Emirates Power Company) and 40% owned by CMS. Financial close for the project was achieved in April 1999.

The leveled average price over the twenty-year term of the PWPA is around 9f/kWh for electricity and 11.7 AED per thousand gallons for water, including the cost of fuel at present prices.

ECPC has entered into a US$ 596 million facility agreement with a syndicate of international banks, headed by Barclays Bank PLC as the "Facility Agent", and by Barclays Capital as the "Lead Arranger", to finance the construction and commissioning of the Al Taweelah A-2 Facility (Emirates CMS Power Company Bulletin).

1.2.4 Regulatory Body

1.2.4.1 Establishment and role of the Bureau

Law No (2) established the Bureau as the sector's independent regulatory body and defines its studies, functions and powers. Article 48 of Law No (2) states: "The Regulation and Supervision Bureau shall have sole and exclusive authority to regulate the water and electricity sector in the Emirate and shall have full powers to regulate all licensed operators economically and technically in accordance with this law."

Statutory appointment of Bureau members is by the Chairman of ADWEA. The Bureau's costs are recovered from an annual fee charged to all licensees. (Annual Report-1999).

1.2.5 Outcome of Emirates Privatisation

- Tariff reduced by 40%. After realizing the benefit of this concept, Taweelah 1A was taken up subsequently and the BOT approach of privatisation is being used.
- More local financiers coming forward to invest in this sector as their built-in fears for various risk factors have been alleviated due to the transparent functioning of Taweelah A2.
- The private company proved their credibility by delivering the goods in time, building the plant in time with good standard and achieving the target of meeting summer peak load.

1.2.6 Lessons Learned From Case Study

From the various literature reviews, discussions and interviews with the water sector authorities (Brantley, Cunneen), the following useful lessons have been learnt.

- The more efficient the sector is, the lower the subsidy, because it lowers the cost incurred in meeting the demands.
- One of the best ways to improve efficiency is to introduce competition in the field. Market restructuring is essential to achieve this goal.
- Introduce incentives and transparency in every stage of transaction by having an independent regulator to monitor the situation.
- Risk factors for the private sector should be reduced wherever possible, as they are investing huge amounts initially expecting recovery only during the complete contract period.
- Introduce a law for governing the privatisation market structure and bring Regulator into action as an independent body. The independent function of the regulator reduces the risk factor and encourages the investors to enter into the market.
- Government should allow the business of the private sector to move forward without any intervention. This also reduces the risk factor for the private sector.
- If the private sector is given incentives and the right to manage the company within a price control, costs will be reduced.
- A multi-skill approach to training O & M staff helps to reduce the manpower required. The plant is now operated with 87 persons while similar plants require about 350 to 400 persons elsewhere. This strategy reduced the cost of operation of the plant and thereby reduced the tariff.
- Contract specification should clearly spell out the obligations. This will minimize conflict and risk factors to the government.
- Shaikh Zaid said that one of his objectives was to help privatisation to assist in dealing with the corruption problem.
- The success of privatisation in the Emirates opens up the opportunities to local firms to take part with confidence in future.

1.2.7 Conclusion

Taweelah A2 is one of the very few privately financed electric generation projects in the Middle East, and the world's first privately financed electricity generation and water desalination project. The transparency and commitment to deadlines demonstrated by this project have been rightly praised. Before privatisation, the cost of electricity was about 20 fils/kwh and cost of water was 18 Dirhams per 1000 gallons of water; after privatisation it is 9 fils and 11 Dirhams respectively. This obviously demonstrates that the decision to privatize the sector was therefore the right approach.

1.3 CASE STUDY IN PHILIPPINES

1.3.1 Introduction

During the period from 15th May to 17th May 2001, we had very useful discussions and interviews with the water authorities in Manila, including key figures in the water sector and some members of the Regulatory Board, Concessionaires and Consultants.

The dramatic experience of the power of private sector participation that helped the government to overcome the power crisis of blackouts in 1992 to 1993, laid the groundwork for the privatisation of Metropolitan Waterworks and Sewerage System (MWSS). Soon after the recovery from the power crisis, the government felt that if the country could be so successful in solving the problem of power through BOT projects, why could they not do the same with water? Could they divide MWSS operation into district units that could be bid out as BOT projects? (Dumol, 2000).

This case study covers the systematic approach of privatisation of water supply and distribution system and the challenges faced by the authorities during the process of implementation.

1.3.2 Operational Activities of MWSS

Metropolitan Waterworks and Sewerage System (MWSS) is the government corporation responsible for the supply of drinking water and the sewerage system. Ninety-eight percent of the water supply comes from the Angat Dam built on the river Angat. The water supply area covers 14 adjoining cities and the municipalities with a population of about 11 million people over 2,000 square kilometers. Roughly 10 million clients live in urban areas and occupy half of the coverage area. The remaining one million customers are in rural areas. Manpower in MWSS was 9 persons per 1000 connections which is one of the highest over staffing record. This ratio in Bangkok is 4.6; Jakarta 7.7; Singapore 2 and Kuala Lumpur 1.1 (David,2000).

MWSS was supplying water to only 2/3 of its coverage population for an average of only 16 hrs per day. Of the roughly 3,000 million liters per day that it received from Angot reservoir, about 56% of it was non-revenue water, and this figure has been actually worsening for more than a decade in spite of numerous attempts to reduce it. With respect to sewerage, MWSS service was only provided to 8% of its population (Dumol, 2000).

1.3.3 Privatisation of MWSS

This privatisation of MWSS is the initiative of President Ramos, who solved the electrical power crisis successfully. He took a special interest and followed up the privatisation process stage by stage.

The success of privatisation in the water industry in Argentina encouraged the Philippine government to follow the same path. To assist them in their planning and execution of water privatisation, the government obtained copies of the documents used by their Argentine counterparts.

Constraints for Privatisation in MWSS

The main constraint was the time limitation for the privatisation of MWSS. The entire process needed to be completed before the beginning of the next Presidential election campaign. This constraint meant that the government would have to work within existing laws, since there was no time to introduce new legislation.

1.3.3.1 Privatisation Strategy Adopted

Since the water sector was plagued by distribution problems, a concession arrangement appeared to be the most effective method for achieving overall privatisation objectives. Accordingly, a 'concession' arrangement was chosen as a wiser method for privatisation.

Splitting the Concession Zones

Following the water privatisation method in Paris, the system was divided into two subdivisions separated by the river Pasig, and two concessionaires were deployed, one on each side of the river. The reasons for splitting the system into two are:

1. Better regulation. If you have only one concessionaire, then he can claim that higher than expected costs are due to normal operational requirements. If more than one concessionaire is competing in the water market, a basis for comparison exists.
2. Competition induces better quality of service, reduction in tariff and natural business pride between the concessionaires.
3. If one of the concessionaires fails to deliver on his end of the contract, then, the other can be asked to take over.
4. One problem associated with two concessionaires is the possibility of two different tariffs for customers living in close proximity to each other.

1.3.3.2 Preparation for Privatisation

Appointment of a Lead Consultant

It was learned that one of the weaknesses of the Buenos Aires transaction was precisely that there were two sets of consultants – one technical and the other financial and with no one to coordinate their work. Therefore, the Philippine group decided to hire one lead consultant who would have overall responsibility for the project. The lead consultant chosen was International Finance Corporation, IFC, a multilateral institution.

Basis for Selection of the Bidder

Strict pre-qualification standards were imposed in order to ensure that only the very best companies would pre-qualify. MWSS would fix service targets and the bidders would submit their technical and financial proposals similar to the two-envelope approach in Argentine. The technical proposal would be evaluated on a pass-fail basis. The financial proposals would be based on the tariff, and the lowest bidder would win (Dumol, 2000).

Water Crisis Act

The Water Crisis Act (WCA), similar to the Power Crisis Act (PCA), was introduced in 1995, granting power to the President to privatize water utilities, including MWSS, and to negotiate BOT contracts to reorganize MWSS in the form of staff reduction through early retirement. This Act did not prescribe any particular provisions, and MWSS was free to create its own procedures. This law also made the theft of water a criminal act, which was to prove extremely important after privatisation (Dumol, 2000).

MWSS employees were reduced from 8,000 to about 6,000 through the offering of attractive compensation packages; more than 30% of the employees accepted the package. (Dumol, 2000)

Necessity to Lower Water Tariff

It makes a lot of political and economic sense to start off with a lower tariff. While it is not absolutely essential, it is nevertheless important for the success of the water privatisation. In order to get the support of the public and the politicians, MWSS was keen to have the bids lower than the existing water tariff. All sorts of things were done to drive the bids to lower tariff.

Other moves carried out towards lowering the tariff were:

- MWSS launched a visible campaign of leak repairs to show the public that it was improving its services.
- In August 1996, about five months before the bid submission, the water tariffs were increased by about 38 percent. This tariff increase was actually long overdue and would have been implemented, regardless of privatisation. Nevertheless, it gave a substantially greater chance that the bids would be lower. More important, it conceptually set the tariffs at the correct level prior to privatisation.
- An automatic tariff adjustment was incorporated in the fifth year to cover funding for sewerage investments at that time. This had the effect of reducing the initial tariffs.
- Arrangements were made for the Department of Finance to provide a performance undertaking, effectively guaranteeing the most crucial commitments on the part of the MWSS. This was probably one of the most important features of the transaction. It gave a lot of comfort to the bidders and their bankers (Dumol, 2000).

1.3.4 Implementation

The President approved the privatisation strategy and recommendations to pursue MWSS privatisation in December 1996.

1.3.4.1 Bid Proposal

Tariff Escalation

One of the norms of the tender document shall be that the formula for tariff escalation should be the same for all concessionaires. It should result in the same projected rate of return, no matter what the value of the variables contained in the formula.

Service Targets

The service targets specified in the Concession Agreement are as in Table 2 (Figures are in percent) (Dumol, 2000):

Table 2: Service Targets of Concession Agreement

Year	1996	2001	2006	2011	2016	2021
Water Service	67	87	98	98	98	98
Sanitation and Sewerage	8	46	55	62	71	83

Ownership and Use of Assets

The concessionaire was granted the rights to use the assets of MWSS, except cash and receivables, at no cost to the concessionaire, provided that the service targets in the concession agreement were met (Dumol, 2000).

Pre-qualification of Bidders

When the initial document was released with the intent of MWSS privatisation, about 50 companies came forward with keen interest. But after going through the tough pre-qualification conditions, finally only 6 operators became eligible for pre-qualification.

The final pre-qualified international water operators and local lead firms were as follows

- International Water (composed of United Utilities of the United Kingdom and Bechtel Corporation of the United States) and Ayala Corporation.
- Lyonnaise des Eaux (France) and Benpres Holdings.
- Compagnie Generale des Eaux (France) and Aboitiz Equity Ventures.
- Anglian Water International (United Kingdom) and Metro Pacific Corporation.

1.3.4.2 Getting Support for Privatisation

• Handling The Politicians and Labor Union

A team of members of congress and labor union leaders was sent to Argentina to get firsthand information from a successful model of the privatisation of the water industry. The outcome was that the labor union leaders were very happy.

• Handling the Media

A steady stream of negative articles were appearing in the media, particularly about the exorbitant $ 6.2 million IFC fee. To counteract this, a local firm was hired by MWSS to carryout public relations work to make media campaign in favor of privatisation to explain the transaction and its potential benefits citing the positive reports on the experience in other countries.

• Bid Opening

The financial bids were opened on 23rd Jan-1997 and results were as in Table No.3.

Table 2: Financial Bids of Various Participants in Manila Concession Contract

	Percent bids	Peso bids
West	Base: 8.77 pesos/cu.met	Pesos/cu.met
Ayala-International Water	28.6333	2.5140
Benpres-Lyonnaise des eaux	**56.5922**	**4.9688**
Abotiz-Compagnie Generale des eaux	56.8800	4.9941
Metro Pacific-Anglian Water Int'l	66.8998	5.8738
East		
Ayala-International water	**26.3886**	**2.3169**
Aboitiz-Compagnie Generale des Eaux	62.8800	5.5209
Metro Pacific-Anglian Water Int'l	64.5080	5,6638
Benpres-Lyonnaise des eaux	69.7888	6.1275

In the above bids, Ayala-International was the lowest in both the East and the west zones. But in order to avoid monopoly by a single concessionaire in both zones and as per the contract condition, Ayala-International, a consortium composed of the Ayala Corporation, United Utilities, Bechtel Corporation, and BPI Capital Corporation became the winner of East zone as the lowest of their bids was in this zone. Accordingly, the Benpres (Lyonnaise des Eaux), being the second lowest in West zone, became the winner of West zone by virtue of the contract condition and finally the President approved the MWSS privatisation bid which was signed on 21st Feb, 1997, the largest water privatisation contract in the world.

1.3.4.3 Functioning of the Concessionaire

Manila East Concessionaire

The company began an aggressive program of repairing leaks, replacing meters and regularizing illegal connections. Non-revenue water (NRW), or the water lost in the distribution system due to leaks and pilferage, went down significantly as result of these major efforts.

Manila Water is currently rehabilitating all major pumping stations, expanding the water distribution network, and upgrading the existing wastewater infrastructure to serve its customers better.

The company will also develop its sewerage system to ensure a more sanitary and healthier environment. New wastewater treatment processes will have no adverse environmental affects (Manila Water Company, Brochure).

Manila West Concessionaire

On January 23, 1997, Maynilad Water Services Incorporated (MWSI), a consortium formed by Benpres Holdings Corporation of the Philippines and Lyonnaise des Eaux of France, won the right to operate water, wastewater and sanitation services of the West Zone of Manila.

Contractual targets

In 1997, the total population of the service area was 7.2 million inhabitants. Non-revenue water (NRW) was 65% at the take-over. MWSI is responsible for increasing water coverage gradually from its current level of 62% of the total population in the West Concession to 98% by year 2021. Sanitation coverage should reach 27% by year 2021 and sewerage coverage should increase from 11% to 66% by year 2021(Lyonnaise Des Eaux brochure).

1.3.5 Regulatory Body

The intention was that of the Regulatory office was to be an independent body, functioning apart from MWSS and the concessionaires. This required legislation to be enacted. Due to the tight schedule for implementing privatisation, there was established a quasi Regulatory Office with the agreement of the contracting parties. The RO's duties were not only to regulate tariff escalation, but also to regulate the concessionaires with respect to all their obligations under the concession contract. The RO is a sort of arbitrator between the concessionaires and MWSS. The R.O. prepared a detailed manual for the concession contract with the help of the consultants, giving better clarity to the contract agreement. The decisions of the RO were approved by the Board of Trustees of MWSS. The operational costs for RO were financed by the concessionaires to MWSS through the Ministry of Finance.

As per CERA (Change in Foreign Exchange Rate Adjustment), the concessionaire is eligible to raise tariffs for any increase in the exchange rate above 2%. The extra amount incurred by the concessionaire due to the exchange rate increase in year one is processed by the RO in year two and subsequently implemented in year three onwards till the end of the concession period. Due to this prolonged recovery period, what today's generation drinks is paid by the future generation.

1.3.6 Outcome of Privatisation and Impacts

From the interviews and discussions with the water sector authorities (Bories, Dumol, Rivera, Tantinco), the people's immediate reaction to the MWSS privatisation has been overwhelmingly positive; they often cite their substantially lower water bills. Although the end result of this splitting was that everyone's water bills went down, some went down more than others. The outcome of the contract was that in the East Zone, mostly occupied by upper socioeconomic groups, the tariff was less than half of the tariff in West Zone, mostly occupied by lower and middle- class groups; this situation created disparity and favored the rich.

As was mentioned before, the contract protects tariff increases due to exchange rate fluctuations only up to a maximum of 2% at a time; due to situations such as the Asian crisis, the exchange rate increased rapidly. At the time of contract, the exchange rate was 26 pesos/dollar while now it is 50 pesos/dollar. This has caused the West Zone concessionaire, who is sharing 90% of the debts of MWSS, a huge debt repayment total, monies which otherwise would have been spent on financing the expansion and improvement of services in their concession area.

Because of the provision in the contract for the East to supply the West a certain amount of water, the fear exists that Benpress (West Zone) could try to cut costs by buying its water from Ayala (East Zone) and subsequently neglect the infrastructure in its own zone.

The leakage problem, which is severe, has not been addressed properly by the concessionaires as it is a long-term project; attention is now being concentrated in the higher-priority areas such as improvement of service, quality and availability. Another reason attributed to the delay in addressing the leakage problem is the delay in one of the major projects of MWSS to supply adequate pressure in the lines to reduce the leakage sources.

Benefits of privatisation

- Water/Sewer rates reduced significantly on Commencement Date
- Water service to reach every citizen within ten years
- 83% sewerage/sanitation service within concession period
- No real increase in water tariffs over the first ten years
- Water pressure and quality to meet international standards in three years
- Non-revenue water to be reduced to 25% over concession period
- Estimated capital expenditures of US$ 7 billion over concession period
- Government subsidy eliminated; instead government to receive about US$ 4 billion in tax revenues over concession period
- MWSS Privatisation is acting as a catalyst for other projects
- Local government units and water districts are seriously looking at private sector participation in some form
- Interest generated in other sectors as well (power, roads, ports, railways, hospitals, etc.)

1.3.7 Lessons Learned from Case Study

- **Define the Problem**

From the experience of MWSS, the root of the problem often lies in the operation and management of the water utility, not the water supply.

- **List the Constraints**

In the case of the MWSS, the main constraint was time. They needed to complete the transaction before the campaign for the next presidential elections started. This constraint meant that they did not have the time to enact new legislation. They needed to work within the existing laws.

- **Identify the Preferred Privatisation Option**

When one knows the available options for dealing with the defined problem and confines oneself within the identified constraints, it is normally not difficult to determine the appropriate privatisation option. Many times, it is quite apparent. There is usually no need to go through a lengthy and complicated decision tree to arrive at the preferred option.

- **Hire a Lead Adviser**

When the moment has come to hire help, especially with complicated work like privatizing a water utility, one needs special skills, knowledge and time. With regard to the selection of advisers, it is most important to select a firm that has actually implemented some form of water privatisation, and to make sure that the particular project manager selected by the firm has likewise had solid experience in water privatisation.

In most cases, the advisers will need to have a variety of skills, necessitating the use of several consulting firms (accountants, economists, engineers, and so on). In this case, it is so difficult to coordinate all these consultants that it is essential to designate one firm as the lead adviser, with full overall responsibility for the project. The service of the lead consultant should be extended further after the signing of the Concession Agreement.

- **Manage the Work of the Adviser**

Even though the adviser's role is indispensable, it is essential that the government always retains control over the process. Advisers do not implement privatisation. The government does it. Some advisers have a tendency to try to fully control the process. This is often a simpler arrangement for them. While this may be simpler, however, it is also ineffective.

While it is undesirable for the advisers to want to totally control the process, it is also incorrect for the government to start dictating everything, without listening to advice. The transaction is a partnership. There needs to be mutual respect between client and adviser.

- **Design the Approval Process**

All government officers who must review the document must be involved in the approval, preferably in one single committee. While it is not the intention to skip any person or office that should be included in the approval process, it requires some form of control over the process by creating a single approving committee. In the case of MWSS, this role was filled by the Special Advisory Committee.

Define the scope of approval by each person or entity. In the case of MWSS, all technical matters were the responsibility of the MWSS Board, legal matters were the responsibility of the Special Advisory Committee, contingent liabilities were the area of the Department of Finance, and so on. Confine each approving party to a particular area.

• **Impose Strict Pre-qualification requirements**
The international water business is relatively new and there are not many players. If a country makes the mistake of allowing unqualified bidders to participate in a privatisation, that transaction may be doomed from the very start.

• **Design a Transparent Bidding Process**
The process must not only be transparent, it must also be perceived as transparent. This perception is crucial to the success of the privatisation. A lot of groups will be scrutinizing the transaction with microscopes, possibly with many predicting failure. (Dumol, 2000).

1.3.8 Conclusion

The long term effects and gains of privatisation of MWSS depend critically on the ability of the Regulatory Office and the residual MWSS to enforce the contractual agreements, anticipate potential problems arising from possible weaknesses in the contract design and changes in the underlying assumptions, data, and analysis used in developing the contract and the technical and financial bids, and to expeditiously implement the necessary adjustments in the contract and mode of operation (David,2000).

MWSS privatisation is considered to be successful due to the following:

- Process was transparent
- Results were accepted by people, politicians, media and courts
- Winning bid prices were extremely favorable
- Winning bidders were among the most financially capable and reputable in the Philippines, and the world.

Confirmed benefits

- Non-revenue water decreased in both zones
- Productivity of leak repair, connection and meter installation/repair crews increased significantly
- Calls/complaints per month increased from 1,000 to 18,000
- Number of personnel reduced.

Other aspects:

- For building confidence in public opinion, politicians are most important. For this, transparency in dealings is the main tool. The role of the media is also vital to the success of privatisation.
- A concession contract is results-oriented and not means-oriented. The means of achieving the result is left to the concessionaire, which gives them the flexibility to arrive at the most economical and technologically suitable methods of implementing privatisation.
- A concession contract is for vast and larger scale projects and it houses several BOTs in it, while a BOT is best suited for well-defined (both technical and financial) projects.
- A concession contract is a long-term partnership between the private and public sectors. The relationship between the two must be cordial, but should maintain some objective distance.

- For the water sector, the concession method is highly recommended, based upon successful models in a number of cases.
- The main challenge in the concession method is establishing an effective regulatory system.
- The Regulatory Agency must balance the interests of the public, the concessionaire and all interested parties and act in a manner that serves all. Binding appeal and impeachment processes should be in place to address disputes that may arise between parties.
- Basic training is essential for Regulatory Agency officials, who should be highly experienced.
- The main risks of a concession contract are political involvement and unstable government policies.
- The concern of the people is not the price but the availability of quality water.

1.4 CASE STUDIES DISCUSSION

Facts are revealed while analyzing the case studies carried out in the above three different countries namely - Argentina, the UAE and the Philippines. It is also to be noted that the details collected from later places provide additional information with better clarity due to the experience gained from place-to-place. It is analogous to the same way; the countries concerned have taken the benefits derived out of other countries privatisation process while implementing their own privatisation programme in their country. For example, Manila water authorities have taken the reference from Argentina that is the forerunner in privatisation of the water sector on a large scale. While analysing the case studies, one would definitely find that there are common features in all countries. Also there are some common features between two countries and some uniqueness in each country as represented by the Figure No.1

There is enough evidence to prove that each country is driven by a necessity to meet the growing demand of water and their financial constraints to meet the requirements. All these governments have some common thing in their approach and their willingness for a change in their policies, and their commitment to stand by their decision is clearly seen. At the same time, there is certain uniqueness in each government is approach to the problem depending on the socio- economic and political environments in each country.

The case studies reveal that there is a need for a consultant who will prepare the required documents and lay a clear road map to show how the country can achieve the results through privatisation. In Argentina, there were two consultants, one for technical and the other financial. In Manila, there was only one lead consultant who was responsible for the overall process right from the beginning. By this way, the water authorities had fixed the responsibility to the consultant so that all matters could be solved without delay. This appears to be a good lesson from the experience of the case studies.

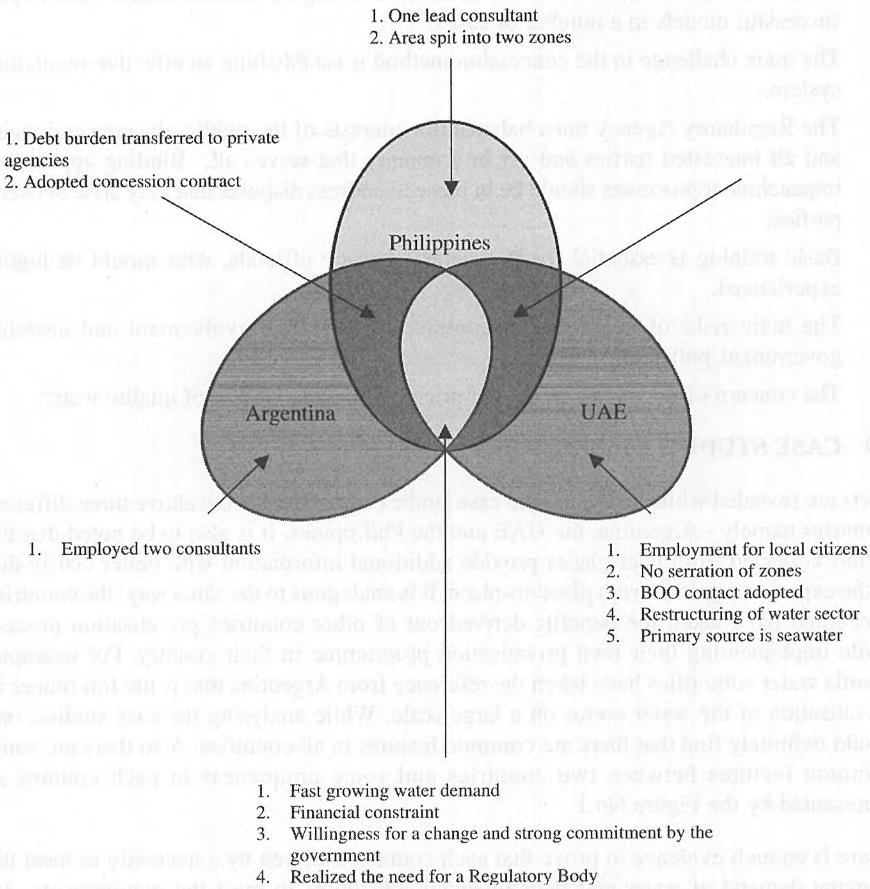

Figure 1: comparison of case studies

Each country has acknowledged the need for a change in the structure of their water sector by opening up fronts for private agencies to enter the market. This is in line with the theory that opportunity should be available for private agencies to participate in the business.

They also understood the importance of a regulatory system through an independent body to oversee the execution and functioning of the newly formed set-up after privatisation. This approach helps to improve the confidence of private agencies to take part in the business. This is another area where the approach falls in tune with the theory in that private agencies should feel comfortable in the business without unnecessary interference from the government side.

The water authorities of Argentina realized the weakness of the system for not forming the regulatory body at the time of restructuring the system. The regulatory body, which is comprised of highly skilled people from the Government and private sectors, would be able to throw more light on the contract terms and conditions at the initial stage itself when the documents are being finalized if they are present in the beginning stage itself. This is one of the lessons that this case study brings out.

In the UAE, the government realized that it was important to strengthen the laws pertaining to multinationals operation in their country and to take care of the integrity of their social culture. Emphasis more in the UAE was on the employment front for their own people so that the social balance is not affected.

Debt burden of the water sector has been successfully passed on to the private agencies in Argentina and Manila that relieved the government from a huge capital allocation from their budget. This is an encouraging factor for any government crunched with heavy financial burden.

Argentina and Manila water authorities resorted to a concession contract with a view to keep the integrity of the system.

In the application of the concession, there are various combinations which will ultimately improve the services and create competitiveness among the players. Like more regulatory bodies and splitting the system into different categories like production, transportation, distribution, etc., for different regions based on geographical and political setups.

In the UAE, the water sector is unbundled into various sections and the contract is executed by the Build-Own-Operate (BOO) method for a period of 20 years in Taweelah A2 plant which is a part of the system. In other words, by unbundling the sector, there is an option to go for either Concession, BOO or BOT approach, which helps to follow the theory.

The situation in the UAE is close to the Kingdom of Saudi Arabia. The supply source is seawater and also the socio-economic and political situation are more or less similar. There is an uniqueness in the UAE because of the way of unbundling and restructuring of the water sector. These could be vital and useful information while deciding on the restructuring of the water sector in the Kingdom of Saudi Arabia. The major difference in the Kingdom of Saudi Arabia is the vast area with major cities in different locations and the source of water spread on either side of the country. Taking into account to this geographical condition, a suitable structure model is to be proposed for the Kingdom of Saudi Arabia. At the same, time the lessons learned from Argentina and the Philippines (mainly in the field of splitting of zones, consultancy services, concession contract, etc.), give valuable guidance while deciding the process to the followed in the Kingdom of Saudi Arabia.

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Public-private partnership: Trends and experiences GCC perspective and pragmatic approach

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PUBLIC-PRIVATE PARTNERSHIP: TRENDS AND EXPERIENCES GCC PERSPECTIVE AND PRAGMATIC APPROACH

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ABSTRACT

The world has been experiencing a shortage of available water, mainly in poor countries. Such a shortage of safe water is contributing to increased poverty and the spreading of diseases. Most water distribution operations in developing countries are managed by the public sector. There is a notion that to be more effective in running the water sector, the private sector should be involved. More reliance on the private sector to manage the water sector has started to take shape. Experimentation has taken place already in many countries. The proponents of the private sectors' involvement in the water sector have had very good arguments concerning making water availability more widespread with a relative increase in water rates. On the other hand, the proponent of the public sector maintains that shifting operational control to the private sector would mean higher rates and less water availability to the poor. The paper will provide a brief assessment of both arguments regarding the management of the water sector. The experiences of several countries participating in some form of privatization within the water sector will be presented as well. The paper will focus on the GCC countries' effort in the water sectors' public-private partnership ("PPP"). It will also present the rationale for their actions and the interest of private companies to participate in the partnership activities in the GCC countries. The paper concluded that the Public-Private Partnerships are moving forward in the GCC and are expanding to provide more water to meet the accelerated demand. The financing is being made from the region's resources. More focus should be placed on contract formulation to avoid disagreement.

Keywords: Distribution; Foreign Companies; GCC; Private Sector; Private Companies; Public-Private Partnership ; PPP ; Water.

Introduction

The shortage of available water worldwide is attracting more attention now than ever before. There are so many organizations that are proponents for the good use of water, such as the World Water Council, and there are organizations that list water issues among the areas of importance to them. The world gathers every three years under the World Water Forum umbrella to discuss water issues. The first was in Marrakech, Morocco in 1997 and the fourth is going to be in Mexico City, Mexico in 2006. The main concern would be how to handle this scarce resource and the best use of it considering the population growth and the increasing need for more water. The impact of such a shortage is being examined by its implication on the increasing level of poverty, spreading of diseases and sometimes an early death.

The issue of water resource management becomes more pressing when we note that there is a shortage even when we have water in abundance. Fredrik Segerfeldt wrote, "In Cherrapunji, India[1] the wettest place on earth suffers from recurrent water shortage"[2]. The point is that shortage is sometimes caused by poor policies and management as it was suggested, "We use a mere 8 percent of the water available for human consumption instead bad policies are the main problem"[3].

The option for public or private management of water resources will be examined. There are many considerations to take into account. Both arguments will be presented. While the partnership between public and private interests is being currently implemented a brief disclosure of its success and failur will be presented from selected cases.

The GCC countries are experiencing what the rest of the world is struggling with, the water shortage. The shortage is prompted by the increase in the population and the increase in the level of economic activity in the region. While there is an obvious reliance on the process of desalination in the region, the cost of this process is placing a burden on the national budget of the countries that select this alternative. Therefore, the trend in Public-Private Partnership will be addressed with some thoughts as to the interest and progress being achieved.

Public-Private Partnership

The Water Shortage

The issue of a water shortage is not a new one. There are more than 1.1 billion people without access to clean water and they are mainly in poor countries[4]. The point is, shortage exists and we have many indicators to substantiate this fact. The shortage has had a horrendous impact on the lives of billions of people which have led to widespread disease and an increase in the mortality rate. The economic impact on these same countries is

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1 It is the World's second highest recorded average annual precipitation, 450 in (11,430 mm) over 74-year period exceeded only by the 460 in recorded at Mt. Waialeala, Hawaii. (Britannica on line)

2 Fredrick Segerfeldt, "Private Water Saves Lives," Times media limited. August 26, 2005.(from LexisNexis)

3 Ibid

4 Fredrick Segerfeldt, "Private Water Saves Lives," Times media limited. August 26, 2005.(from LexisNexis)

well founded. A good percentage of water is being used for agricultural purposes. Roughly worldwide, 67 percent is used for agricultural purposes in addition to another 23 percent which is used for industrial purposes while domestic purposes use only 8 percent[5].

The industrial usage is placing a burden and contributing to the pressure on the available resources. Some examples (Table1) will illustrate the point[6]:

Table1: some examples about required water in some industries

In Order to Generate:		Required Amount of Water:
One barrel of crude oil		1,800 gallons
One ton of steel		62,000 gallons
One semi-conductor		3,000 gallons

Based on the fact that water shortage is becoming a universally challenging phenomenon, we turn to the issue of how this problem is going to be addressed and how to provide alternatives to lessen the hardship of its impact.

The Current Constraints

Aging Infrastructure. Depending on the region there is an acknowledgement that the facility infrastructure is aging and the rehabilitation efforts are either slow or not done properly because of the high cost. In addition, most countries are raising their water quality standards to insure a higher health standard. There is always a concern about the financial funding and in many cases the lack of it. For example, in the United States, one estimate indicated "a $300 – $800 billions funding gap over the next 20 years to repair aging infrastructure at the nation's 16,000 wastewater treatment and 40,000 drinking water facilities"[7]. Other countries are facing similar problems. Logically, you have a system that has been running for so many years with limited rehabilitation and are mostly owned by public utilities. These utilities are subjected to the typical process of budgeting and bureaucratic procedures which add cost and extended time to reach resolutions.

The Water Standard. With the advancement of research we are becoming more aware of certain impediments. Therefore, the standards are being upgraded. While the health side is being improved and nobody will argue against it, there is a cost attached to the upgrade in standards. Industrialized countries can afford to absorb such additional cost but the poor countries are struggling with that extra cost.

The Budget. The budgetary constraints are universal. There is no country that does not have limitation as to how much they can afford to spend on water management.

With the above limitations and constraints, there was a need for a private partner who was willing to share in the management and get compensated for its effort as any other private

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5 "Assessment of the Role of the Private Sector in the Development and Management of Water Supply in Selected ESCWA Member Countries", U.N. ESCWA, October 3, 2003 , P.11

6 Steven Loranger, "The Water Century", the Globalist. March 04, 2005

7 "Budget Cuts Could Spur Private-Public Partnerships", Natural Resources, Vol. 10, No. 9, July 25, 2005. (from LexisNexis)

entity would. The balancing of risks and rewards is crucial to the survival of private interests. Several pioneering companies got involved in the process with reasonable success, which helped to open the door to more involvement by the private sector.

Public-Private Partnership Participation Models

The emergence of private participation in public sector projects came into play during the last twenty years. Private participation was implemented in several countries with varied degrees of success. The assessment of these activities is not based only on financial grounds but rather on other emotional and political grounds as well.

The International Network on Participatory Irrigation Management provided a good Public-Private Partnership Participation model which could be summarized below Table2 [8]

Table2: Public-Private Partnership Participation Model

Type of Contract	Duration (Years)	Responsibility of the Operator	Payment of the Operator	Asset Ownership
Service Contract	3 – 5	Specific Task (Billing, etc.)	Fixed Fee	Public
Management Contract	3 – 8	Some O&M Functions	Fee with Incentives	Public
Lease/ Affermage	8 – 15	Some O&M; Exclusive of Investments	Percent of Tariff Collected	Public
Concession/ BOT	20 – 30	All O&M; Plus Investments	Contractual Tariff	Public
Divestiture	Indefinite	All O&M Inclusive of Investments	Customer Tariff	Private

It is clear from the above table that the available options are: management contract, lease/ affermage and concession/BOT. They constitute the forms of Public-Private Partnership that could be considered in this regard. The service contract and the divesture are two extreme cases. One is just an assignment contract and the other is transferring/selling the assets to a private company, which is rare in the water sector.

In evaluating the options, we have to keep in mind that the domain of water management was always considered as a public domain. Also, the notion is that the public sector can afford providing water by subsidizing the real cost of water and in order to do that, "some municipalities kept rates artificially low by using revenue from other sources."[9]These are the realities we face especially in the developing countries.

Some Sector Characteristics. No matter what our views are on the subject of the private sector's involvement, the following table (Table3) gives an idea about the characteristics of the water sector and the differences between developing and developed countries,

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8 Eight International Seminars on PIM-Highlight (May 9-12, 2005) (from inpim.org)

9 Romy Varghese, "For Sale by Owner", The Morning Call, September 5, 2005 (from LexisNexis)

10 Nicola Tynan and Bill Kingdom, "View A Water Scorecard", Note Number 242, April 2002. The World Bank Group.

including some of the industry's target goals. With these indicators in mind, private companies are looking into their involvement in the sector[10].

Table 3 Charecteristics of the water sector between developing and developed Countries

Indicator	Unit	Target	Developing	Developed
Unaccounted - for Water	Percent	<23	23	16
Staff per 1000 Connections	Person	5	>20	2.1
Personnel Cost / Operating Cost	Percent	n/a	39	29
Working Ratio-Operating Expenses/Collection	Number	0.68	n/a	n/a
Timley Collection	Months	3	8-Apr	1.8
Coverage Rate-Water	Percent	n/a	18-100	100
Coverage Rate-Sewerage	Percent	100	100	n/a
Connection Fees (% per capita GDP)	Percent	<20	n/a	n/a
Water Prices (20 LITER/Day-% Per Capita GDP)	Percent	n/a	0.2	.036 - 0.120
Quality	Hours/Day	24	n/a	n/a
* the target indicators are being achieved by 25 percent of developing countries				

From the above table, it is clear that the Unaccounted-for Water figures are relatively high which is around 23 percent in developing countries and 16 percent in developed countries. The large Unaccounted-for Water figures, place a heavy financial burden on the bottom line of the business. Another fact is that the high Personnel Cost as a percentage of the Operating Cost reaches almost 39 percent in developing countries compared to 29 percent in the developed countries. This indicator suggests high overstaffing in water utilities.

When we look at the Water Prices (prices for 20 liters per day per individual as a percentage of the Per Capita GDP), we find it is 0.2 percent for developing countries while it is 0.036 to 0.12 percent in developed countries. The conclusions are that water prices and final cost takes away a good portion of the consumer's income in developing countries. Due to many factors, utilities are charging a relatively higher price for water compared to the developed countries. So the search for better utilization of resources and the desire to provide water at affordable prices.

As it was mentioned before the process of engaging the private sector was received with a variety of receptions. There are success and failure stories. Few cases from the United States will be cited along with some international ones as well.

Cases of Public Private Partnership

It should be noted that the World Bank was a force in encouraging the opening of the water sector to foreign investors. In some projects, the World Bank was forceful in promoting structural changes within the water sector of the borrowing country. Considering that the World Bank deals primarily with the developing countries, its impact is well felt.

Also, it is noted that there are four major water companies that control 70 percent of the world water market[11], so the arguments for and against the involvement of the private

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11 Ibid

12 Uwe Hoering, "Public Private Partnerships in the Water Sector No Panacea to Solve All Problems." D+C Development and Cooperation (No. 4, July/August 2002) P. 5-17 in Went.

sector are well established and very well debated. The major point to be noted is that "there is no empirical evidence that private companies...are more efficient than public enterprises..."[12]

There is a well documented and interesting case of a Public-Private Partnership in the United States. Consumers consider the Public-Private Partnership to have helped raise their water rates and have decreased the public's control over water management, while the managers of these utilities consider the involvement of the private sector as a reduction in the public cost. Below (Table 4) are sample cases from the United States:

Table 4: Sample Cases from USA of Public-Private Partnership

Ref.	City	Year	Contract	Partner	Results
1	Stockton, CA	2003	20-year	OMI-Thames Water	Saving $3 m/year
2	El Paso County Water Authority, TX	1994	20-year	ECO Resources, Inc	The facility provides water at about 24 cents per 1,000 gallons-US ave. $2
3	Danbury, CT	1997	20-year	Veolia Water North America	rate stability
4	Puerto Rico Aquaduct & Sewer Authority	2000	5-year	Thames Water North America	The plant is regarded as a "model" facility for the Island's water
5	Atlanta	1998	20-year	United Water	termination 2003
	Sources: (1,5)Natural Resources, (2,3,4) from Water Partnership.org.				

While there is a different assessment, the public is moved by the increase in rates, but the overall assessment is that the involvement of the private sector is helping to manage the resources more effectively.

On the international scene, the attitude in New Delhi, for example was against involving the private sector as recently as July 2005, there is a huge movement against the process.[13] In the UK, it was noted by some sources that privatization leads to a dramatic increase in its prices.[14] Thus there is an unpleasant feeling in the air about it.

In Morocco, we have an interesting Public-Private Partnership case from Casablanca. The indicators are that the Moroccan Government delegated the management of its water supply, sanitation and electricity to a private sector consortium named LYDEC since 1997. The thirty-year delegated management contract which is subject to review every five years was considered a success in that it increased the number of population served by more than 20 percent in the savings of water, a significant reduction of flooding risk and the modernizing of customer services[15]. Also, we have a fail story from Cochabamba, Bolivia, where a contract was signed in September, 1999 and canceled in April 2000 after riots and protest due to tariff increase and other factors. So the picture is mixed, but there is more success than failures.

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[13] Sujay Mehdudia, "Opposition to Water Privatization Snowballs", Kasturi&Sons Ltd. (KSL), the Hindu, April 7, 2005 (from LexisNexis).

[14] Pegue Manage, "SNEC's Privatization May Have Negative Consequences". The Post (Zambia)-AAGM (from LexisNexis)

[15] Claude Jamati, "Casablanca (Morocco): An Example of Public-Private Partnership-Water Resources Development, Vol. 19, No. 2, 153-158, June 2003

The trend toward more Public-Private Partnerships is being advanced in many parts of the world, regardless the negative attitude that we read about it. Recently, Algeria's expressed interest in having co-managers for its water resources. It was stated that foreign players will be allowed to manage water networks according to a contract with the state and without having the authority to fix water prices. [16]

Another reason to advance the Public-Private Partnership is that there is also a concern in the public sector over financial sustainability, including the capabilities to meet needs for investment and devise a fee settlement method for full coverage of the costs, of such organizations in every corner of the globe.[17] Therefore, the argument in that the Public-Private Partnership is here to stay carries more weight. The need of rehabilitation of the infrastructure system along with its heavy cost will place a heavy burden on the budget of the country. This sentiment is being felt in countries around the globe.

The Gulf Cooperation Council Countries

The Current Situation. The Middle East and North Africa region (MENA) which the GCC is part of, has approximately five percent of the world's population, but less than 1 percent of the world's renewable fresh water supplies. To illustrate the point of such a limitation, the following table (Table5) lists the available internal water by cubic meters per capita in the GCC countries:

Table5: Available Water m^3/capita in GCC countries

Country	Cubic Meters Per Capita
Bahrain	n/a
Kuwait	10
Oman	n/a
Qatar	94
Saudi Arabia	118
UAE	58

Source: Renewable Water Resources, World Almanac & Book of Facts, 2005, P. 179

It is clear that the GCC countries are relying more and more on desalination, which is becoming wide spread worldwide. Just to name a few states in the United States, we have the states of California, Florida, Texas and Massachusetts who are rather active in desalination activities.

What needs to be remembered is that the agricultural sector, which accounts for 87 percent of water use in the region, is characterized by high water wastage. Water prices for agricultural use and water prices for residential use recover less than 50 percent and 75 percent respectfully, of operations and maintenance cost. Water subsidies represent 10 percent of the government expenditures in Egypt, 8 percent in Yemen and 3 percent in Iran.[18] Just for illustrative purposes, Kuwait spends KD 238m (USD 830m) a year to keep the price of water low.[19]

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16 'Algeria Opens up Water Sector to Foreign Investors, Al-Bawaba Reporters, July 7, 2005 (lexis by Comtex News Network, Inc.

17 Public Private Partnership (PPP), "Water Voice" Project Report, march 2003, The Secretariat of the 3rd World Water Forum, P. 160

18 World Bank MNA P. 9

19 "Kuwait MPs Criticise Water Rationing", Middle East News Online, April 2004.

Water demand escalated from 5 billion cubic meters (bcm) in 1970 to about 30 bcm in 2000.[20] These were driven by agricultural consumption (85 percent of the total water used) and by rapid urban expansion (14 percent).

Economic growth in the GCC is extremely good, in Oman 12.5 percent; UAE grew by 8 percent in 2004 while Saudi Arabia grew at 5.3 percent. [21] So opportunities for private sector investment exist through the infrastructure sector including water. Population growth and youth are pressing the needs for additional capacity and modernization. [22] Water resources require substantial expansion and modernization.[23]

All of the above factors induced the GCC countries to find ways to generate more water to meet the demand and make consumers more aware of the value of water. Noting the high cost of subsidizing water in the GCC as we saw in the case of Kuwait. Having said that, the process of Public-Private Partnership has been taking shape in the GCC countries for sometime now. Initially, most of these countries provided water to their inhabitants at a highly subsidized rate. With the increase in the population, a more careful analysis is being conducted. The idea of involving the private sector became a reality in several of the GCC countries.

Below a brief list of activities in the GCC countries:

Saudi Arabia. One of the major undertakings is in Saudi Arabia where the government is looking for Independent Water and Power Producers (IWPPs) to provide a large proportion of new generating electric capacity and drinking water, the initial plan calls for four IWPPs, and each is expected to cost $1 billion. The government hopes to offer 60 percent stake in each of the four projects to private companies. The following table (Table 6) gives some basic information about the new expected capacity for the water part of the plants: [24]

Table6: Expected Capacities of some water plants in Saudi Arabia

Location	Million Gallon per Day
Jubail	75
Ras AL Zour	176
Shouaiba	176
Shuqaiq	23

UAE. The United Arab Emirates was a pioneer in the arena of Public-Private Partnership in the water and power sector. In the Emirate of Abu Dhabi, a contract was awarded for the construction of Taweelah A2 to a joint venture of EMS Energy Corporation (40 percent) and the Abu Dhabi Water and Electricity (60 percent). Another consortium of Total and

20 "The 7th Gulf Water Conference", (from KISR)

21 Terry A. Newendrop and Ramesh Raman, Privatization and PPP in the Middle East., Taylor-dejongh. P. 1 (from Taylor-dejongh)

22 Ibid

23 Ibid

24 **Neil Ford, Middle East, Jan 2005 Issue 352, P. 38-39 (EBSCO)**

Tractebel has been awarded a $1.5 billion contract to expand Taweelah A1. The Consortium owns 40 percent while Abu Dhabi Water and Electricity owns 60 percent of the project.[25] In the Emirate of Ajman, an international tender for $140 million was awarded for a water concession.[26]

Oman. In Oman, an international tender of $417 million was awarded for Barkal IWPP.[27]

Kuwait. In Kuwait, the region's largest wastewater BOT scheme is being built at a cost of $375 million. The Utilities Development Company (UDC) and Ionics of the United States will build and operate the 375-million-litres-per-day plant over the 30-year concession period[28]

Qatar. Qatar embarked on Public-Private Partnership initiative in the water supply sector with the power generation and water Desalination Company of Ras Laffan with a capital of $750 million. The company will operate as a joint venture between the Qatari Electricity and Water Company (25 percent) and International Independent Power Producers (55 percent) with the government owning the remaining 20 percent. The QEWC will purchase all the electrical power and water.[29] QEWC signed a Memorandum of Understanding (MOU) with the Water Reuse Promotion Center (WRPC) of Japan to build an experimental desalination plant at Dukhan QR 18m ($5m), to produce 200 cubic meters of potable water a day. The plant is to be utilized for research purposes.[30]

From the above brief survey of major undertaking in the GCC, we see the drive towards implementing the Public-Private Partnership at a speed which matches the plans of these countries to move forward in that direction. The trend is definitely towards making better use of the available natural resources and to install the conservation attitude in the minds of the consumers. Years of subsidizing water in addition to other commodities like electricity and the below market prices for oil and gas, resulted in a noticeable drainage of the government purse and the misuse of these scarce resources. If you drive around in any major city in the GCC you will find the above observation to be accurate. The cost of unchecked use of water needs to be reassessed. But in the mean time, to have the private sector get involved requires effort on the part of both the public and the private parties. Simply put, the deal must be attractive for the private sector to get involved. Foreign companies are interested in participation with an interest to manage and to promote their technologies and products. But the financing is resting on the countries in question.

Conclusions and Recommendations

The water shortage is a universally challenging phenomenon. The severity varies from region to region. While the shortage could be due to natural elements, there is a thought that this shortage is caused by poor policies of those stewards of the sector.

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25 "Assessment of the Role of the Private sector in the Development and Management of Water Supply in Selected ESCWA Member Countries", ESCWA, October 3, 2003. P 31.

26 Newendrop and Raman. P.3

27 Ibid

28 Sulaibiya Wastewater Plant, Kuwait. (from Hal crow)

29 "Assessment of the Role of the Private Sector in the Development and Management of Water Supply in Selected ESCWA Member Countries", U.N. ESCWA, October 3, 2003 , P 31

30 WWW.qewc.com

The heavy agricultural usage of water is universal too. It is true as well that no one in the GCC countries recovers the cost of water, thus the need for subsidies which in turn would impact the national budget. The expanding trend of increasing industrial projects in the region simply requires more water.

The cost of rehabilitating the infrastructure is heavy. In the United States, the funding gap is between $300–$800 billion over the next twenty years. In the Arabian Peninsula, there is a need of $30 billion for replacing the desalination facilities.[31] The cost is high, and the need is there. The type of partnership could be grouped under management, lease or concession. There is no simple formula for a made-in-heaven contract. Most are hybrids which take into consideration many factors, namely the condition of the infrastructure and the ability of the consumers to pay. It was noted that there are four major companies in the world that controls 70 percent of the market, so there is a bulk of experience in the market place and lots of models of partnerships. The experience of the Public-Private Partnership is mixed. The point is there is more positive than negative, but in the meantime, let us agree with the notion that the subject is controversial and it will stay as such for a long time until the parties manage to articulate their positions more and make a concentrated effort to make it a success.

The case in the GCC countries is similar to the rest of the world with the exception that their governments are not financially under pressure like most countries. They have to rely to a large degree on desalination. They became an expert world-wide in the desalination industry. The recent GCC meeting of the water Ministers indicated the thinking about the prospects of linking the member states with a water network and have taken desalination as a strategic choice for them[32]. The countries are experiencing an increase in population, coupled with progressive economic growth and an increase in industrialized activities, thus the need for more innovative ways to address the shortage issue.

The GCC are moving in steady steps toward more involvement in the Public-Private Partnership. While the UAE took the lead in that respect, Saudi Arabia, Oman, Kuwait, Qatar and Bahrain are taking consistent steps in that direction. There is optimism that the Public-Private Partnership is good for all concerned.

While it is being done, it is suggested to have the following points in mind while we are moving on the road to accelerate the Public-Private Partnership in the GCC.

- The objectives of both parties to the partnership should be spelled out clearly and discussed in detail to assure a clear understanding of each party's goals.
- The public party should conduct thorough due diligence before engaging the private party in a transaction. A real assessment should cover all aspects

[31] "Assessment of the Role of the Private Sector in the Development and Management of Water Supply in Selected ESCWA Member Countries", U.N. ESCWA, October 3, 2003 , P 24

[32] Mariam Al Hakeem, "GCC Ministers to Tackle Issue of Water Scarcity", Gulf News, September 15, 2005 (from LexisNexis)

of technical and financial track records to assure that the party is more than qualified to engage in the process.

- The contract should be tailored to the specific case. Many factors are special to that particular situation. Nature of the assignment (i.e. management, lease, etc), the size of the customer's base and the condition of the infrastructure. So, no ready-made contracts. Therefore, there is a need for a good legal team to draft a contract that will last without the need to go through the court system to enforce.
- Targets for both parties should be spelled out clearly. They should be measurable targets so assessment of the progress in achieving them can be quantified.
- While setting up the tariffs, a thorough study should be conducted to assess its suitability to the kind of customers being served. If need be, having a progressive tariff system (heavy user pay higher prices). The satisfaction of customers with the tariff is a must for the success of the partnership.
- Customers should be informed periodically as to the status of the partnership. Also, they should be informed as to the consumption levels of water as well, to make them more conscious of its value.
- Like in any business venture and especially for a long term one, it is important to assess and reassess the progress periodically and make the necessary adjustment to maintain healthy relationships which will impact the bottom line and thus the customer satisfaction.
- At the end it is important to keep in mind what William Bullein, the British writer said in 1562 A.D., "water is a very good servant, but it is a cruel master".[33]

Acknowledgments

I would like to thank Kareem G. Nakshbendi for his assistance and the University of Maryland University College Library for its support and assistance.

[33] Steven Loranger, "The Water Century", the Globalist. March 04, 2005

The opportunities for water resources management in the Emirate of Abu Dhabi, United Arab Emirates

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THE OPPORTUNITIES FOR WATER RESOURCES MANAGEMENT IN THE EMIRATE OF ABU DHABI, UNITED ARAB EMIRATES

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ABSTRACT

One of the six main environmental goals of the Environment Research and Wildlife Development Agency in Abu Dhabi is a management regime for water resources. The development of a Water Management Strategy for the Emirate commenced in 2003 and is due for completion in 2007. With the Emirate's current annual water use twenty six times larger than the annual renewable resources, and with one of the highest per capita consumption rates globally, there is an urgent need for the implementation of programmes and projects to improve water management and rationalize water use. This paper describes the current water situation and water management issues in the Emirate and describes the work of the agency in developing a water management plan whose objectives are to help "manage the overall water resources of the Emirate of Abu Dhabi in a sustainable, economically viable and environmentally sound way that will allow the long-term socio-economic development of the Emirate of Abu Dhabi".

Keywords: Abu Dhabi Emirate, Water Management, Water Consumption, Challenges

Introduction

The Abu Dhabi Emirate, one of the seven Emirates which comprise the United Arab Emirates (UAE), occupies an area of about 67,000 km², or about 80% of the total area of UAE (Figure.1)

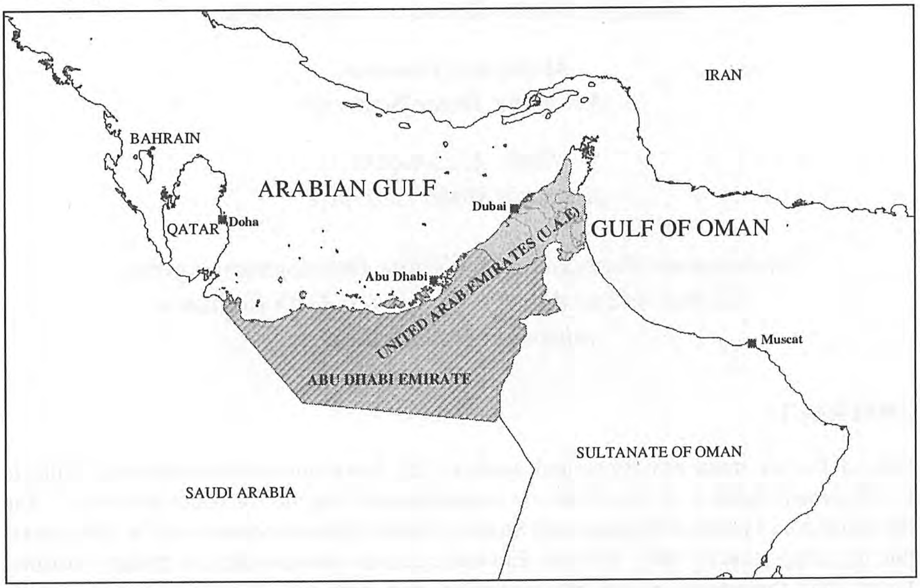

Figure 1: Location of Abu Dhabi Emirate, UAE

The Environmental Research and Wildlife Development Agency (ERWDA), based in Abu Dhabi, was established in 1996 and in the year 2000 was designated as the "competent authority" for environmental issues in the Emirate of Abu Dhabi. One of the six strategic goals which comprise the current ERWDA environmental strategy action plan for the Emirate of Abu Dhabi, 2003-2007, is "a management regime for water resources". A working group for water management was established between ERWDA and numerous stakeholders in 2001 when a preliminary strategy development study was undertaken. (Joudeh, 2001). The current 5–year action plan for the development of a water resources management strategy was approved in 2003 (ERWDA, 2004).

The first stage of ERWDA's action plan in satisfying its strategic goal of developing and implementing a water resources management plan for the Emirate of Abu Dhabi is baseline information and ambient monitoring (Brook 2003). The overall plan adopted has been modelled on that recommended by the World Bank (Le Moigne 1994). ERWDA's work has identified all missing information and a process to fill all the gaps of missing information has been closely followed, including collaborative well inventory projects and the development of a GIS water database (Dawoud et al, 2005). Activities proposed for the first two years have now been completed (Table 1) and scenarios and options for water management are now being studied. As part of its efforts of public awareness and dissemination of water information, an annual ERWDA water resources statistics bulletin has been produced for the last three years (ERWDA, 2005).

Table 1: Water Resources Management Strategy Implementation Plan

Year	Step	Activities
1 & 2	Baseline Information and Database Development	1. Studies review, compilation and analysis of data. 2. Well inventory and database development. 3. Water balances and groundwater resources evaluation. 4. Predictive modeling, monitoring network review and in-house capacity training
2	Management Scenarios and Options	1. Technical arrangements to meet physical development of water resources. 2. Institutional and human resources. 3. Regulations for enforcement. 4. Demand management sector use. 5. International agreements e.g. trans-boundary water resources. 6. Environmental and heath protection. Comparison of options
3	Management Strategy	1. Strategy developed from choice of most suitable options analyzed 2. Time allocated for debate by Government 3. Involvement of all stakeholders
4 & 5	Implementation and Monitoring	1. Program schedule for all tasks with stakeholder responsibilities. 2. Monitoring and enforcement of strategy. 3. Appointment of enforcement agency

Water Resources

Groundwater, despite its heavy utilization over the last 30 years, still provides the majority of the water source for the Abu Dhabi Emirate. The aquifers developed to date are primarily unconsolidated, Quaternary sands and alluvium found at depths of generally less than 50 -100m below ground level. A total of 253,000 Mm^3 occurs as a resource (Hutchinson, 1996), but only 7% is fresh, the remainder is brackish or saline. Fresh groundwater, with salinity of less than 1500 mg/l TDS, occurs in belts along the Eastern region on the border with Oman and also as a large basin in the Liwa – Beda Zayed area. (Al Bady, 1999 and Rizk et al. 2003). Figure 2 shows the general groundwater salinity within the upper, surficial, alluvium and sand aquifers throughout the Emirate.

Groundwater generally originates as recharge from rainfall runoff in the eastern region and moves West and North- West towards the Arabian Gulf where it discharges into sabkhas and the sea. This regional flow process takes more than 15,000 years. A detailed evaluation of groundwater resources in Abu Dhabi can be found elsewhere (Rizk et al., 1997).

According to 2003 statistics (ERWDA, 2005), groundwater constitutes 79% (78.5% brackish, 0.5% Fresh) of all the Emirate's sources, followed by desalinated seawater (17%) and treated wastewater (4%). Groundwater is mostly used in agriculture, forestry and amenity/ recreation irrigation. In the absence of a national well inventory and a process for well registration, the total number of production wells abstracting groundwater is unknown, but is thought to be more than 100,000. Only a small amount of groundwater is abstracted for municipal drinking water supply (potable well fields are now found only in the Eastern Al Ain region; 15 well fields contribute only 4% of the total domestic water supply requirements), however, there are still a large number of private household wells which abstract water for domestic use.

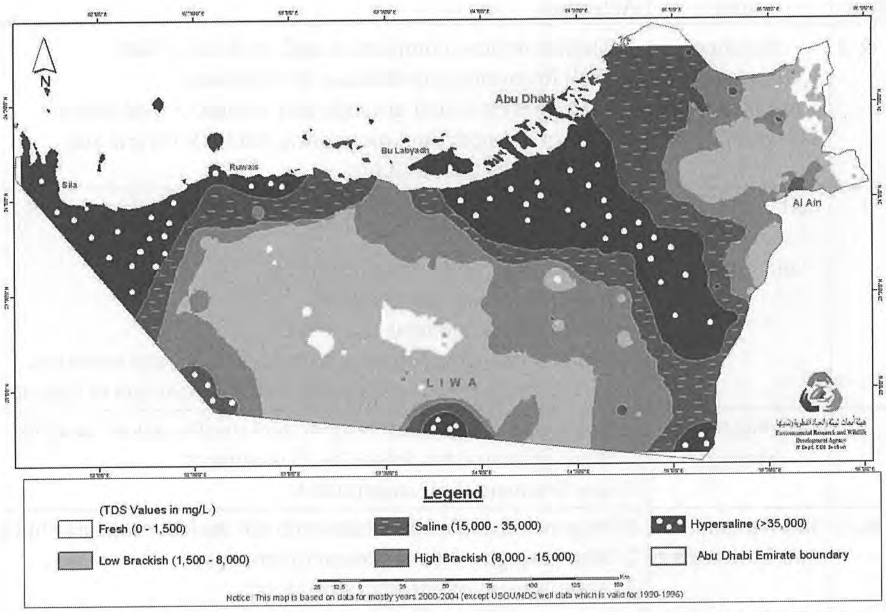

Figure 2: Groundwater Salinity of the Shallow Aquifers of Abu Dhabi Emirate

Given declining water levels and a general deterioration in groundwater quality, the protection and conservation of all groundwater of all qualities is of vital importance. The potential for enhancement of recharge to groundwater by way of building dams has been studied but the Abu Dhabi topography is not generally suitable for the construction of recharge dams. In fact, only one recharge structure, a diversion bund with several downstream recharge basins, exists in the Emirate. The more mountainous terrain of the Northern Emirates is far more suitable for their construction; more than 60 dams have been constructed with a combined capacity of greater than 140 Mm^3.

Water Production

An analysis of all water produced shows that the majority (79%) is groundwater abstracted from boreholes and shallow hand dug wells, the remainder is produced from desalination of seawater (17%) and from 23 sewage treatment plants (4%). Desalinated water is produced from five main plants, four situated along the Arabian Gulf coastline at Mirfa, Abu Dhabi, Um al Naar and Taweelah and one on the Gulf of Oman at Qidfa, Fujairah. The latter commenced production in late 2003 and provided for the first inter-Emirate transfer of water. Abu Dhabi Emirate will use its allocation of the produced water from Fujairah in the domestic, agriculture and forestry sectors. In the agriculture sector, desalinated water is now blended with in-situ, indigenous brackish groundwater in order to produce an overall water quality which will allow for the irrigation of a much larger variety of vegetables and fruits than at present. This ultimate improvement in water quality, brought about by the new policy of blending water from different sources, allows for improved on-site farm management and cultivation of higher value crops for the market place.

The largest sewage treatment plant is located at Mafraq, 40km southeast from Abu Dhabi City, which treats all domestic and industrial sewer mains waste for Abu Dhabi Island and surroundings, catering for a population in excess of 500,000. Generally, a large proportion of all domestic and industrial wastewater is treated and re-used, but this forms only about 4% of all water produced.

Due to declining water tables, there are now no totally natural flowing aflaj systems (traditional irrigation canals used for agriculture in oasis areas of Al Ain) left in the Emirate; all those operating are either fully or partially supplemented from groundwater which is abstracted from nearby wells drilled within the oasis areas. This situation contrasts sharply with that found in the neighboring Sultanate of Oman, where a total of 4254 aflaj were inventoried in the year 2000, of which 72% flowed naturally without any support.

Water used for domestic purposes in the Emirate is abstracted from 15 wellfields, but the bulk is supplied from the five main desalination plants described above, plus small, inland desalination units (typical capacity <100m3/d) which treat brackish water in the region south of Al Ain. Due to the recent extension of potable water transmission lines south of Al Ain; these 25 small desalination plants are now being gradually phased out.

Water Consumption

Figure 3 shows sources and users of water resources in Abu Dhabi Emirate. Water is consumed in the domestic, industrial, commercial, agricultural, forestry and amenity sectors. Water of drinking quality, which meets the Abu Dhabi Emirates standards (RSB,2004), as specified by the Regulation and Supervisory Bureau, is supplied for domestic, industrial and commercial use and accounts for 17% of the total water resource consumed. Government policies to date have encouraged the general "greening" of the Emirate's desert landscape and in 2003, a total of 6% of the total area of the Emirate may be considered as "green" and supported by some means of irrigation. Although consumption has reduced slightly since 2002, by far the largest user (58%) of water is the agricultural sector, comprising nearly 25,000 small citizens farms and a few, large state farms (cereals) whose numbers have been declining in recent years. The citizens farms are irrigated by over 50,000 productive wells. Water used in this sector is mostly brackish in quality, and almost exclusively groundwater. The second largest user of water is the Forestry sector (18%) comprising over 300,000 hectares distributed between 250 separate plantations and irrigated by over 5500 wells. Like agriculture, most of the water used is brackish groundwater, but in some cases, higher than sea-water salinity groundwater is used for irrigation. The overall percentage of the total water resources used in this sector has increased from 16% in 2002 to 18% in 2003.

Amenity irrigation for parks, gardens and recreational areas, e.g. golf courses etc., accounts for just over 7% of the total 2003 consumption, slightly less than the previous year. This sector relies mostly on treated effluent as a source, but wells are also utilized. Finally, the Industrial/Commercial sector, whilst expanding, still accounts for only 1.5% of all water consumed. Industries are located in a small number of dedicated Industrial Estates in both the Eastern and Western regions.

Compared with the 2002 water resources statistics, 2003 shows an overall increase of 5% in total water resource consumption for the Emirate; domestic consumption has increased from 441 to 522 million cubic meters (MCM) and forestry from 512 to 607 MCM, but

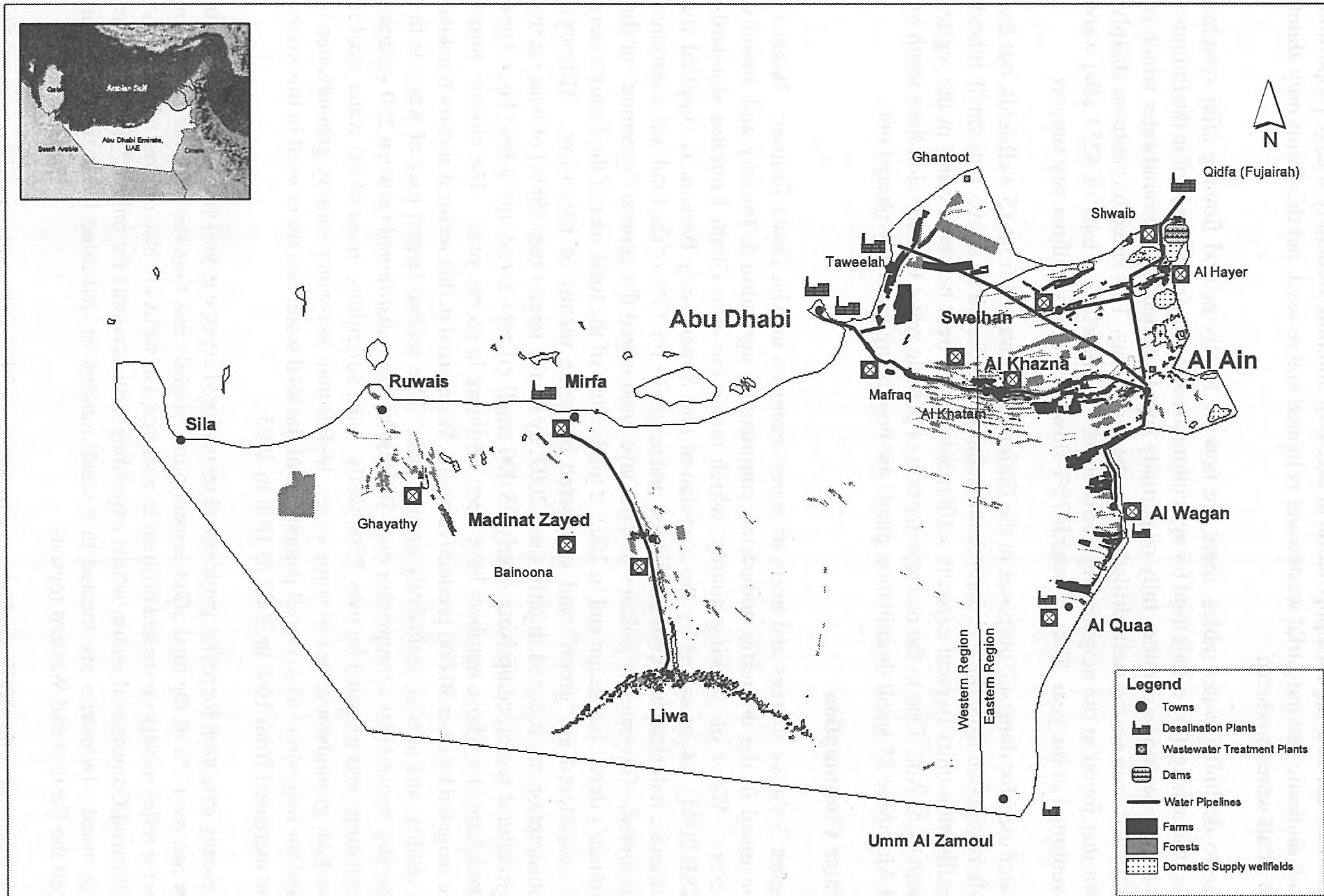

Figure 3: Sources and Users of Water in Abu Dhabi Emirate

there have been small recorded reductions of 1% and 5% in the agriculture and amenity sectors respectively. A smaller consumption in the agriculture sector is as a result of a policy to reduce the area under irrigation in large state farms; the 2002 irrigated area of 24,000 ha reduced to 17,000 ha in 2003. The Emirates 2003 total water consumption is shown in Table 2 below.

Table 2: 2003 Water consumption summaries

	EASTERN REGION (Mm3)	%	WESTERN REGION (Mm3)	%	TOTAL (Mm3)	% TOTAL	% CHANGE SINCE 2002
Domestic	136.87	9.16	385.13	20.41	**522.00**	**15.44**	**+18**
Industry	15.21	1.02	42.79	2.27	**58.00**	**1.72**	**0%**
Agriculture	1109.07	74.19	840.29	44.54	**1949.36**	**57.64**	**-1%**
Forestry	122.85	8.22	484.45	25.68	**607.30**	**17.96**	**+18%**
Amenity	111.00	7.42	134.04	7.10	**245.04**	**7.25**	**-5%**
TOTAL	1495	100	1886.70	100	**3381.70**	**100**	**+5%**

N.B see Figure 3 for definition of the "regions" of the Emirate.

Water Management Issues

An investigation into the water situation and current water management operations in all the water use sectors in the Abu Dhabi Emirate over the last three years has shown that there are now many realistic opportunities for developing new processes, programs and activities which should significantly improve water resources management overall.

General requirements for effective management of water resources in the Arabian Peninsula have recently been compiled as guidelines for the GCC countries (Brook et al, 2005). These requirements are centred on the following, major principles:

- Institutional and Management
- Social
- Economic and Financial
- Environmental
- Information, Education and Communication
- Technological

The following aspects of water management have been studied as an ongoing process through several collaborative projects and other activities as part of ERWDA efforts in developing a water resources management strategy and action plan for the Emirate of Abu Dhabi:

- Water use: policy, planning and regulation
- Protection, conservation and monitoring of water resources
- Water data and information management
- Groundwater exploration and assessment
- Local, regional and International cooperation and collaboration
- Strategic emergency water resources

Common to the solution of most of the problems and difficulties associated with various aspects of water management in the above categories is the ultimate requirement for the establishment of a central, independent authority for Water Management. At present, responsibility for managing water sources and water use is divided between several organisations and agencies. This fragmented arrangement is unsatisfactory for effective water management and would be significantly improved by consolidating and amalgamating the efforts of the various water sector users in water management activities. There are strong arguments for this requirement in other GCC countries as well.

In the field of water use policy, planning and regulation, the following observations have been made for the Abu Dhabi Emirate:

- A general reduction in quantity and quality of groundwater through over-abstraction in certain areas, resulting in increasing groundwater salinities and the salinization of land leading to a reduction in crop yields and sometimes to the abandonment of some farms.
- Over-irrigation resulting in local drainage problems
- Unplanned development in the farming and forestry sectors
- Restrictions imposed on the Forestry Sector due to insufficient water and poor irrigation water quality
- Minimal water demand management, especially in the agriculture sector
- Lack of recognition of the true economic cost of water when assigning its use
- Uncontrolled and unregulated groundwater abstractions through well drilling, with no well registration or contractor registration procedures

In the field of water resources protection, conservation and monitoring, the Emirate is disadvantaged by:

- The absence of a coordinated Emirate-wide water resources monitoring network and programme
- Incidences of groundwater nitrate pollution due to fertilizer use
- Lack of groundwater protection policies, e.g. no protection zones for municipal wellfields that still produce drinking water
- Incomplete records, little on-site monitoring or measurement of water resources, especially whilst drilling new wells, and lack of inventories on sources and demands
- Lack of qualified, technical, on-site supervision, monitoring and data collection during drilling and general water resources monitoring
- General waste of water and leakages

In terms of water data and information management, there is non-availability or poor access to water resources information and data in some water use sectors, a general lack of monitoring in the agriculture sector, especially for groundwater abstraction and lack of a central, Emirate-wide database to hold and analyse water resources data and information. No national well inventory has ever been undertaken and there is poor data collection when drilling new wells.

Detailed groundwater exploration and assessment programmes have been completed in the past and these need to be expanded and continued, especially for assessing deeper aquifer potential and a better coordination and collaboration between programmes is required.

The Emirate also, like most GCC countries, suffers from little or no technical cooperation with neighbouring countries, especially on developments on or near to international boundaries.

Conclusions

ERWDA, as the competent body for the protection and conservation of natural resources in the Emirate of Abu Dhabi, has embarked on an ambitious program of collaborative projects and activities over the last three years aimed at improved water management in all water use sectors.

A detailed assessment of the current water situation in the Emirate shows that the consumption of water continues to increase (currently at 5% annually) and yet the naturally renewable water resources account for only 4% of the total annual water consumption, the remainder being supplied by mining from mostly brackish groundwater resources (79%), the desalination of sea water (17%) and the treatment and re-use of wastewater (4%). A large and expensive program of commissioning new desalination plants is required in order to keep up with the increasing demands for drinking water, since the yields of existing potable well fields is declining. Groundwater levels continue to fall and have now resulted in the drying up of all the natural falaj systems in the Emirate, which are now either supported by onsite, deep boreholes or imported desalinated water, via long and expensive transmission pipelines. Increasing demands for fresh water in the Eastern Region of the Emirate has resulted in the first inter-emirate transfer of water i.e. the new Fujairah Qidfa desalination plant now supplies part of its allocation to the Abu Dhabi Emirate via a 180km transmission line

The Emirate's record of treating and re-using both domestic and industrial waste is excellent, with an almost 100% treated and re-use record in the major cities, but the produced water supplies only 4% of the total consumption. Groundwater remains by far the largest source of water and, despite its uncontrolled and unregulated use in the past, still accounts for almost 80% of total demands. Given the increasing lowering of groundwater levels, and steady trends in increasing salinity, the requirement for its protection and conservation has now reached paramount levels and this issue is currently being addressed at the highest level of government.

ERWDA's ambitious program of collaborative projects and focussed activities over the last three years, since the inception of its Water Resources Program within the Terrestrial Environment Research Centre, has highlighted all the major issues and challenges faced with managing the Emirates water resources, but there are three areas which are proposed for priority work, namely regulation and control of groundwater abstraction, through a well registration and permitting policy, the establishment and management of a comprehensive water resources monitoring network and the establishment, management and maintenance of a central water information network, based on a GIS database. The successful completion of these priority projects will provide a sound basis for water management in the Emirate. Other challenges for water management, which are also extremely important, are the rationalisation of water use, especially in the agriculture and forestry sectors, a program of continued public awareness and education for water conservation, prevention of groundwater pollution and protection of existing potable well fields, raising the level of technical cooperation and collaboration with neighbouring

Emirates and states, the development and management of strategic water reserves and also institutional development and capacity building which will be essential for the long term development and implementation of water management in the Emirate of Abu Dhabi

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A Millenarian Water-Rights System and Water – Markets in Oman

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A MILLENARIAN WATER-RIGHTS SYSTEM AND WATER-MARKETS IN OMAN

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ABSTRACT

Water rights and water markets may appear as relatively new ideas at the international level. They are considered as a key management instrument to improve water use efficiency and to secure users' access to water. It is considered that a successful water management transfer to users requires a clear recognition of water rights. Centuries ago, water scarcity in Oman led to the development of a system of water allocation based on water rights. While no one can use falaj water for irrigation without holding a water right, all falaj community members have free access to water for domestic purposes, from the head of the canal, provided it is taken in recipients and not pumped. Three categories of water rights co-exist, private, common and quasi-public. Water rights are independent of land property and are issued in perpetuity and transferred from one generation to another via inheritance. The right is usually expressed as a timeshare called Athar corresponding to an approximate ½ hour share per water turn. Aflaj and wells exploit the same groundwater; thereby seniority has been established to protect falaj owners and was implemented by the falaj community. The provision of electricity to rural areas and the availability of water pumps encouraged the development of tube wells which resulted in the drying of number of important falaj. In 1983, The "State Consultative Council" declared a radius of 3.5 km around falaj motherwells to be protected zone but few resources were committed to the execution of this central legislation which is supposed to be implemented by the State rather than falaj communities. The most frequent market consists on the lease of common property water rights through auctions which provides income for falaj maintenance and administration. Water rights sale is less frequent and concerns only private rights. The enforcement of water rights is undertaken by the water users community independently of State intervention. Both the existence of water rights and the management system explain largely the perpetuation of Aflaj over centuries albeit it consists of small holders.

KEYWORDS: Groundwater, management, common water rights, seniority, small holders.

INTRODUCTION

Water rights and water markets may appear as relatively new ideas at the international level. Experiences in the USA date back to the 1970's, while the first introduction of water rights in a developing country dates back to 1981 in Chile (Thobani, 1998). Since then, several countries such as Mexico, South Africa, and Australia has followed the steps and introduced water rights (CRP, 2003). Water rights are considered as a key water management instrument to improve water use efficiency (Rosegrant, 1993; Garduno, 2001). Meinzen-Dick and Bruns (2000) reported that the top priority of water user associations in some countries that undertook the irrigation management transfer (IMT) reform was clarifying and strengthening the water rights. Vermillion (1997) considers that for IMT to succeed, a clear recognition of water rights is required. Water rights are considered as a means to secure access to water. However, water scarcity in Oman led centuries ago to the development of a system of water allocation based on water rights. The management system is known as falaj, where water rights are treated similarly to real property rights that are inherited, sold, and rented in the same manner independently of the land on which the water originates, or on which it is used. Water rights are in use for small scale subsistence farms where IMT transfer has been a failure elsewhere (Easter and Zekri, 2004), and water rights are also common in similar irrigation systems such as qanat in Iran, Syria and Yemen (Honari (1989); Lightfoot (1996, 2000)). Many voices are mounting against the establishment of private water rights and water markets. Dellapena (2001) argues that water can not be owned in the usual sense of private goods because its uses generate spill over effects that are not reflected in market prices. He stresses that markets in water are not frequent because when water markets do exist they transfer small quantities among closely located farmers with little effects on third parties. Lastly, he argues that the attribution of marketable water rights may result in a concentration of power in the hands of non-elected elite exacerbating the unequal distribution of income by rent creation. Trawick (2003) argues that privatisation is not recommended where tiny properties prevail as is the case in the mountainous areas of Latin America. Bauer (1997) argues that the absence of the "beneficial use" doctrine, that is "use it or lose it" principle is leading to an inefficient use of water despite the implementation of water rights that are supposed to increase efficiency. Owners of water rights are holding more rights than they might use. But Bauer recognizes that irrigators are holding excess water rights mainly for three reasons: first, weather uncertainties leading to uncertainty in water availability makes tree-crop growers hold excess water rights for repetitive drought periods; second, future expectation of higher water right prices compared to current low prices; and third, it seems that water is not scarce enough in Chile to stimulate trade and prevent holding excess water rights. There is no data on how much water is really "sleeping" in relative terms. Does it constitute a serious problem to water markets? Compared to the ex-ante market implementation, have the "sleeper" water rights increased? Will the absence of "sleeper" water rights cause misuse of water over time? In 1996, a law was passed in Chile allowing the public agency to charge a fee for non-use of water rights. Any rights not used for a period of five consecutive years could be taxed, which leaves room for handling repetitive drought risks in a Mediterranean climate. Such a law does not affect crop-tree growers whose excess holding of water rights is a strategy to deal with risk. Thus, such a law is intended to resolve market inefficiency using economic instruments rather than blaming the water market.

Even if water markets span over centuries in Oman comprehensive studies about water rights, the corner stone of water markets, are almost inexistent except the study by Caponera (1978). Most of the studies on falaj were oriented towards the hydrological aspects and description of the irrigation schemes and farming system (Wilkinson, 1977; Dutton, 1989; Haydar and Omezzine, 1996). In this paper a review of the aflaj water rights will be highlighted. Aspects such as management and administrative structure will be illustrated. The most salient characteristics of recent water rights through international experiences will be stressed. The paper ends with recommendations to update the millenarian Omani water rights system.

FALAJ TYPES

The word falaj (plural aflaj) means a traditional water network comprised of man-made underground water galleries transporting groundwater which services a village community and an irrigation area. Three main types of falaj are in existence in Oman, these are:

- Ghaili falaj consists of a perennial flow in the surface gravels of the wadi or river. The flow is diverted into a man made channel either by a flow bund, or through a short collector gallery. Sometimes, Ghaili falaj are simple diversion channels that bring the water directly from the wadi to the nearby gardens (Wilkinson, 1977).

- Daudi falaj. Water of these falaj is dug from the underground aquifer. The water is conveyed to the village by an underground tunnel that may reach up to 17 km (Rawas et al, 2000). Daudi Aflaj are characterized by a relatively high flow of water discharge and have the most stable water flow rate around the year compared to the two other types of falaj.

- For Aini falaj, water is drawn from one or more natural springs. Like Daudi, the water is transported from the springs by a channel up to the agricultural land MRMEW (2002).

IMPORTANCE OF AFLAJ WATER

Currently Oman depends on both groundwater and desalination for supply of fresh water. Sub-surface and deep wells are the main sources of water for agricultural use. Desalinated water is restricted for urban uses and is estimated at 100 million m3 per year (MHEW, 2004). The first desalination plants were built in Muscat and Masirah in 1976 (MHEW, 2002). The first domestic water pipe system in Muscat dates back to 1968 and relied on groundwater pumping (Caponera, 1978). Currently groundwater renewable volume is estimated at 900 million m3, 93% of which is used in agriculture (Zabet, 2005): 38% of groundwater is used via Aflaj and the remaining 62% are exploited through individual wells (MRMEW, 2002). The provision of subsidized electricity to rural areas and the availability of cheap water pumps resulted in an increased number of individual tube wells drawing from the same aquifer, which resulted in the over pumping of groundwater. Several aflaj went dry. In addition, seawater intrusion into fresh groundwater became a serious threat in coastal areas. The government responded by constructing dams to speedup the recharge of aquifers and reduce the severity of the problem. Dams could not be used directly for surface water provision to substitute groundwater pumping because of the very high evaporation rates caused by extremely high temperatures and low rainfall.

Table 1 summarizes annual water demand and cropped irrigated area for the three types of falaj at national level. Traditional aflaj irrigation area corresponds to 38 % of the total cropped irrigated area. The last aflaj census reported 4,112 flaj in Oman (MRMEW, 2002).

Most of the censed falaj are Ghaili accounting for 48 %, 24 % are Daudi and Aini represent 28 %. It is worth noting that despite the fact that Ghaili constitute the majority of the total aflaj, they only irrigate 9 % of the total cropped area and Daudi and Aini irrigate 22 % and 12 % of the area respectively. This can be attributed to the fact that Ghaili are usually seasonal due to their dependence on shallow subterranean sources that dry out during dry seasons (Al Rawas, 2000). In contrast, Aini and Daudi falaj water emanates from relatively deeper groundwater tables. Thus, water flowing from the Daudi type is more regular than Ghaili. This is further supported by the annual water supply, as shown in Table 1, with Daudi supplying 243 million cubic meters, while Ghaili supply only 97 million cubic meters.

Table 1: Volume of water and irrigated areas per Falaj type in Oman

			Number of Falaj per type			
	Total irrigated Area by Aflaj (Hectare)	% of the cropped area	Daudi	Aini	Ghaili	Total
Total	26498#	38	967	1152	1993	4112
Percent of the total number			24	28	48	100
% of irrigated area*			20	10	8	38
Annual water supply(Mm^3)			243	119	97	459

Source: MRMEW (2002); Al Sarhani (2000)*and MAF (1994) #

Afalj play a major role in the irrigation sector as well as on tourism. The Falaj system is considered an integral part of rural life, upon which the community depends (Haydar and Omezzine, 1996). From a social point of view, falaj used to allow fund raising for local community needs such as schools, mosques and charity for the needy through rent of common property of land and water rights (Al Shaqsy, 1996). Finally, aflaj form an enchanting oasis environment in the middle of the desert within and around which people build their houses and develop their activities. This is to stress the multi-functionality of water in the falaj system. The social structure played a major role in the long existence and management of the system. Sutton (1984) pointed out that many of the systems at presently in operation are over a thousand years old, and owe their continued existence to the well- established social and financial structures.

DOCTRINE OF WATER RIGHTS IN OMAN

In 1988, Royal decree 83/88 vested water rights in the state. However, the use of water in aflaj in Oman is governed by the water right ownership. The essence of the ownership is that while no one can use falaj water for irrigation without holding a water right, all village community members have a free access to water for domestic purposes. This could be interpreted as a protection of basic human needs to access water while assuring protection of water rights for production ends in order to insure the best use of this scarce and valuable resource. However, other reasons may explain the free access for domestic uses. Community members can take from the main channel the water they need for domestic uses without being connected by pipes or diverting the water flow from its channel. As a result, the quantities used for domestic purposes are insignificant compared to total falaj volume of water. Therefore it is easier and less costly to allow free access to water than to enforce a fee for domestic water and complicate the management of the falaj system. Besides, those who live in the falaj are either water right holders or farmers renting water rights thus having the right of access to water in all circumstances. This means that they take water almost proportionally to the water rights they hold. It is to be stressed that even non-community members have free access to falaj water for human uses. This means that water cannot be refused to humans or animals to slake their thirst and the protection of basic needs prevails over the appropriation of water. Moreover, the poorest are even offered some help from quasi public falaj water rights returns. These considerations reflect the advanced vision of the water rights doctrine. In fact, the doctrine takes into account efficiency via the attribution of water rights for production purposes as well as equity and social consideration allowing free access for domestic purposes not only to falaj community members but also for anyone who needs water for basic drinking purposes.

TYPES OF WATER RIGHTS

Water rights may be classified into three categories.

- Private water rights. These can be either explicit water rights with property licenses or implicit without written licenses owned by individuals. The difference between the two categories is mainly the opportunity to trade water. In fact, for the implicit water rights, the right is exclusively a use right that could be inherited but in no case traded or even rented; it is tied to land property.

- Common water rights. These are water rights owned by falaj community members. These rights are mainly established to generate income for falaj maintenance and operation expenditures. The common water rights are rented weekly, half yearly, or on an annual basis through water lease auctions. This type of common water rights is of great importance since it aims to prevent the free riding problem in relation to the cost recovery of maintenance of the water system. By pooling together a set of water rights, based on a percentage of individual shares into a common property right owned and rented by the falaj's manager, it provides a continuous monetary flow. It is important to note that this is the particular originality of the Omani falaj system management in comparison with similar water systems such as the ones in North Africa and Asia Minor called Klettara, Foggara and Qanats (Garduno-Velasco, 2001).

- Quasi public water rights owned by charity institutions, now under state control. The returns from the rent of rights are used to finance mosques, schools and needy people. These water rights are managed in the same way as common water right, that is by a falaj manager. The quasi public water rights could not be sold but could be only leased in short term markets. Consequently, these water rights may increase by donations of private water rights, but never decrease.

Most Ghaili falaj are linked with the implicit water right or water use right. This can be attributed to the fact that Ghaili falaj are usually seasonal due to their dependence on shallow aquifers that are depleted during dry seasons. Therefore, sitting rights without written license reflects such seasonality and lower level of security. On the opposite, Daudi and Aini falaj are characterized by explicit defined water rights with property licenses.

Table2. Water rights distribution for a sample of falaj

Falaj type	Falaj Name	Private rights %	Common rights %	Quasi public rights %	Total Number of owners
Daudi	Al Malki	78	10.5	11.5	116
	Al Hali	77.8	11.4	11.1	98
	Al Maiser	70	11.1	18.9	167
Mean		**75.1**	**11**	**13.8**	
Ghaili	Samdi	98.7	1.3	0	1500
	Farsaki	95.4	3.3	1.3	450
	Dykali	90	10	0	150
Mean		**94.7**	**4.87**	**0.4**	
Aini	Al Hajeer	95.5	0	4.5	336
	Al Kasfa	97.2	0	2.8	
Mean		96.4		**3.7**	
Overall mean		**87.8**	**6.0**	**6.3**	

Source: Al-Ghafri (2004); Al-Shaqsy (1996) and authors Survey (2004)

Table 2 shows the distribution of water rights ownership for a sample of a falaj. By far, the most significant category hold is private ownership, accounting for a range from 70% to 98.7%, with an overall mean of 87.8 %. Common property represents approximately 4 to 11 %, with an average of 6 %. Finally, quasi public ownership ranges from 0 to 18 %, with an average of 6.3 % for the considered sample. A wide variation in ownership type among the three types of falaj is observed. For instance, Ghaili hold the highest proportion of private ownership water right. In contrast, Daudi accounts for 13.8 % of quasi public owned water rights. Daudi falaj also has the highest common property right with 11 %. This can be attributed to the fact that Daudi maintenance and operation costs are much higher than Ghaili or Aini falaj's costs which consequently necessitates relatively more common water rights and returns to cover the costs.

CHARACTERISTICS OF OMANI WATER RIGHTS

Some aflaj in Oman date back to several centuries BC (Al-Salmi, 1981). There is no consensus on whether relatively new falaj are created by private or public investments. Some authors report government support and intervention in the creation of new falaj. For instance, Al-Abri cites the creation of 4 falaj during the late 1600's as public projects. Rights are established in proportion to the participation of each person in the construction of the falaj. Al-Ghafri (2004) pointed out that after the construction of falaj, participants create a committee of experienced people to distribute water shares among themselves. Water rights systems date back to several centuries and they are in force for all falaj independently of the fact that these were promoted by public funds or private funds. The following summarizes the water rights characteristics on the traditional aflaj system in Oman.

Separation from Land

Ownership of water is often independent of land property in falaj in Oman. The objective of this separation is to allow water to be exchanged freely among farmers.

Duration

Water rights are issued in perpetuity and are transferred from one generation to another via inheritance.

Privacy

Falaj water rights are recognized at the national level and have the same legal aspects as any other private asset. Thus, a water right may be sold, inherited, or donated for charity organizations. Sale of water rights are done through signed contracts. A copy of the contract is given to the falaj manager who holds the records and transactions of water rights in a register.

Proportionality

The water right is usually expressed as a timeshare of the resource on per rotational irrigation cycle. The most common water right is the Athar, a timeshare, which corresponds to an approximate ½ an hour share per water cycle. Such a share embodies the principle of sharing of available supplies and shortfalls as the falaj flow rate fluctuates according to seasons and years. Besides, during drought periods, when the flow of water is low, the length of the water cycle is usually extended to avoid water losses in channels (from 7 to 10 days for instance). It is important to note here the significance of using timeshare rather than volume to measure water right. The use of timeshare instead of volume allows more management flexibility when dealing with uncertain water flow, i.e. change occurs in the length of the cycle rather than volume of water distributed which needs reliable metering and re-estimation of individual volumes.

Seniority or Priority

The physical structural layout of the falaj main channels gives priority for domestic water uses. Domestic water is free access at the main source. Nobody is allowed to access water in other locations of the channel. This restriction is imposed probably for two reasons. The first reason is health and water quality, since the channels are open andwater is exposed to pollution mainly by animals. The second reason is equity that is drinking water should be taken before water is divided among water right holders to avoid specific shareholders being affected by the intake. Common bathing facilities are also accessible for free, and water is recycled into the main canal since no soaps are allowed for bathing. No diversion of falaj for private purposes is permitted in the residential area. However, diversions for public institutions may take place such as for a fort, mosque or school. For irrigation, water distribution is done according to the water right duration and the schedule supervised by the manager which stipulates the exact timing and day of the week for each water right.

Since wells and falaj exploit the same groundwater seniority has been established to protect falaj owners; that is, the rights that were acquired first in time are given the absolute priority. This seniority is implemented through an exclusion zone around every falaj's mother well, main canal and secondary canals. Customary laws were commonly used as a legislative tool to declare such protected areas which extend over a 25 meter radius around falaj infrastructure where well digging is not allowed because it affects the falaj flow (Caponera, 1978). The control and surveillance of the protected area was the responsibility of the falaj's community. Recent literature (Al-Sarhani, (2000); Al-Shaqusi

(1996); MWRE (1996)) referred to such zones as the Afalj Protected Zone. The intensive drilling of new wells during the period 1975 to 1989 caused the drying of hundreds of falaj and new legislation was needed. In October 1987 the "State Consultative Council" declared a radius of 3.5 km to be falaj protected zone Al-Sarhani (2000). However, few resources were committed to the execution of this "central" legislation which has to be implemented by the State rather than falaj communities. Consequently, the falaj census (2002) shows that the percentage of dry (or dead) falaj is compared to 1992 data. That drought has exacerbated depletion of groundwater is not contested. However, drought in Oman is a recurrent phenomena and the falaj community used to managing it. The main and most important variable explaining falaj dryness is the increased drilling of wells which in turn is the consequence of an inability to protect the seniority principle of water rights in practice. It has been observed that in recent dried falaj, farmers are buying water from individual well owners situated around falaj, when available, to preserve their palm tree plantations. Consequently, protection of falaj water rights depend heavily on the implementation of the seniority principle and regulation of groundwater extraction to unsure the sustainability of the system.

Transferability

The most frequent markets of water rights are among farmers within one single community. Water transfer to other irrigation communities down stream is practiced when an existing infrastructure allows it. No transfers of water for domestic or industrial uses are reported or observed. The absence of water transfer to urban uses could be explained by the fact that cities are relatively new dating back to the 1980's and were planned based on government intervention through heavily subsidized desalinated sea water provision.

WATER RIGHTS' MANAGEMENT

The administrative structure of a falaj is an independent entity constituted, for the large falaj, by a manager, a cashier, an agent in charge of water distribution and a technician specialized in the maintenance of the physical structure (COA, 1995). The manager is called "Wakeel" in Arabic which encompasses the term procurator. Wakeel is a legally authorized person to manage the affairs of a falaj's commonly owned water rights. The manager is elected among the community of water rights owners. The Wakeel's role is not restricted to the full authority in trading common water rights, but he also makes decisions regarding operation and maintenance (O&M) of the falaj. He reports to falaj shareholders on expenses and returns on a yearly basis. When water lease returns do not cover O&M costs the difference is paid by shareholders proportionately to the water rights owned. The manager receives 5% to 7% of water lease returns for his services. Moreover, Al-Abri reports that when returns from common water-rights rent exceed O&M costs the manager, after discussion with falaj members, can take the decision on investing the funds in assets which in turn will be included in the community belongings and managed by wakeel[1]. Al-Gafri and Norman (2001) added that the Wakeel also solves water conflicts between farmers.

[1] Accumulated funds are taxed (Zakat law) at 2.5% per year if not invested which encourages people to invest.

Water rights' markets

Aflaj water markets in Oman are active and span several centuries. These markets can be divided into two main categories. A market for the sale of water rights and another market for short term lease. The unit used in the market is the Athar which corresponds to an approximate ½ hour per water cycle and it is not based on volume. The timeshare arrangement makes it difficult to compare prices among falaj and even within a single falaj as the water flow varies from one season to another, even though a number of studies have mentioned large variations in water right prices for both sale and lease markets. Wilkinson (1977) mentioned that the prices of water depend on falaj flow, weekly versus yearly leases, on seasons and whether it is a day or night timeshare. Al- Shaqsy (1996) added the number of participants in the auction as an explanatory variable, since as more people participate, a tougher competition results in higher prices.

Water rights sale

Water rights sale concerns only private rights that usually take place in case of inheritance and thus are not frequent. Sales fall under the form of auctions usually in the village main market. At any stage during the auction, the seller can withdraw if he considers that insufficient bidders are present or if he considers that the final price is non satisfactory. Generally, however, attempts to persuade the seller to accept the arrived-at price will be made not only by the buyer but by the auctioneer as well. When the transaction is agreed on, a contract is established between the two parties explicitly expresses the transfer of the water right. It is the responsibility of the auctioneer to make sure that the seller receives his money from the buyer. Payment is usually made in cash. The auctioneer receives a percentage of the price as a compensation of the advertising and auctioning efforts.

Common property rights' market

Short term markets are based on auctions also. Rented water rights' auctions deal with falaj common property rights. Common property rights are the main source of income for falaj maintenance. These water shares are usually auctioned by lots of an Athar. Short term auctions are usually conducted in the same common water market place at the village level and at an agreed on time, normally on Friday afternoon, a rest day in Oman. The auction assembles the following participators:

- The manager who acts as a procurator on the common property rights
- The buyers or farmers
- The auctioneer
- The recorder, responsible to record the buyers names and the final bidding price

Every falaj has a book serving to register the water leases' prices, buyer's name as well as the date and duration of each lease.

Private water rights' market

The same auctioning principle applies to the private water rights market as for the common property water rights. The difference, however, is that the seller represents himself. This type of auction occurs in the village's market place. Such auctions take place occasionally at the will of the seller and not periodically. So, we can say that there exists two separate lease markets, one for common rights regularly scheduled on a place called the water market, and the second taking place sporadically in the village's market place.

WATER RIGHTS AND THE INTERNATIONAL EXPERIENCES

Although a number of countries have already adopted water rights in their legislation, there are still some misunderstandings and fears about the issue. The most important fear In what follow the salient features of water rights, based on the experiences of several countries are exposed.

Access rights

In most countries, water is still considered as a public property, even in the USA (Colorado, California), but access or use rights are allocated as a private property. In the literature these access rights are treated and considered as property rights, since the major characteristic of these access rights is the exclusion of other users. Using the term access right rather than property right will probably ease the move in the LDC to the establishment of water rights since water codes include water as public property and there is a reluctance in changing this statement.

Separation from land

A key feature of water right is its separation from land ownership. This is the major step that should be taken in order to allow the efficient operation of the water market. The objective of this separation is to allow water to be exchanged freely.

Tenure of license

It is preferable that the rights to water will not be limited in time. In Chile and theUSA, they are perpetual. In Mexico, water rights are given for renewable periods varying from 5 to 50 years. In South Africa, the tenure is variable and the maximum period is 40 years. In Australia the legislation varies across the states, some states have limited duration while others have perpetual water rights.

Privacy

Water rights should be recognized at the national level and have the same legal aspects as any other private asset. In Chile and theUSA the titles are fully protected private property rights.

Proportionality

For surface water, rights can be defined as a share of a reservoir or stream flow, with well-defined share and time of access. Due to the uncertainty inherent in water supply, a share is preferred by the public agency rather than a fixed volume of water. Under the share type of right, the uncertainty is placed on the individual rather than the public agency.

Seniority or priority

The priority of the right is the date the water was first diverted. In the Western US, senior water rights are rights that were acquired first in time and are given the absolute priority before fulfilling junior rights, which have been acquired later in time. In Mexico, domestic water rights are given the highest priority. This is also the case in Chile for some urban water companies who benefit from a priority rule, even for the new rights bought from farmers (Hearne, 1998, pp 149). In Australia (New South Wales), the terms used are high security and general security rights and correspond respectively to senior and junior rights (Tan, 2002). The priority rule may make markets more difficult to organize than the proportional rights because of the non-homogeneity of the rights. The key for priority rule market is good information so that the market price can reflect the real difference in the value of different rights.

The allocation of a priority or seniority would prevent water trade and disadvantage farmers since domestic and urban water users usually have priority. The seniority rule is dominant in the USA, as water rights have been allocated progressively over time, as new users demanded these rights. However, in the LDCs where rights are yet to be designated and will likely be attributed at the same time, the seniority concept loses its meaning. For the Mediterranean countries, water is managed mainly through dams with, allocation of rights based on past uses, as shares will be the easiest way to organize the market.

Permanent and contingent water rights

In contrast to the permanent rights, the contingent rights are granted only for higher than normal water flows. Holders of the contingent water rights can use water only when there is excess of water with respect to the demand of permanent right holder's. The contingent right is similar to the junior right and is used only during higher than normal water availability. The contingent water rights are used primarily in case of river management and are less applicable to systems with large dams, since the excess water can then be stored for use later.

Sleeper water rights or "beneficial use" doctrine

Mexico requires that water rights be used at least every three years. This is done to prevent speculators from just holding water rights. But what is the rationality for holding sleeper water rights, that is, rights not being used that could be traded for a positive value? The problem of misuse, if any, could easily be solved, in the irrigation sector, by using a two-part tarification scheme, where the farmer has to pay a fixed amount independently of the volume of water used. The higher the fixed component, the less incentive the farmer has to keep a stock of unused water. In 1996, Chile passed a law allowing the public agency to charge a fee for non-use of water rights. Any rights not used for a period of five years could be taxed, which allows room for handling repetitive drought risks in a Mediterranean climate. But the concept of "beneficial use" is quite fuzzy and can be interpreted differently by the courts, which make sellers less confident and may prevent trading. It appears that the "beneficial use" doctrine is redundant in countries already experiencing water shortages. It can have negative impacts on water trade and cause welfare losses if water sales do not constitute beneficial use. On the other hand, if water rights will be allocated based on past uses, then a good approximation of these uses will certainly avoid the problem of sleeper water rights.

Consumptive and non-consumptive water rights

One of the challenges of sustainability in water use is the interdependence in water uses. Not only is economic efficiency important, but also is the managing of third party effects primarily related to return flow externalities. The problem of consumptive use applies mainly to irrigation water when transferred for non-agricultural uses. This complicates the definition of property rights for farmers. In fact, crops use only part of the total irrigation water applied. The question is whether to allow farmers to sell their total allocated water share or only the consumptive part of it? The experience varies across countries. In Mexico, Australia and the USA, the concessions are based on consumptive use. In Chile and the Colorado Big Thompson Project (CBTP), the rights are granted for full use of the water stipulated in the right; that is both consumptive and non-consumptive water are allowed for trade. Allowing only consumptive water use to be traded is a way to limit water transfer out of the agricultural sector. The actual consumptive water use depends on the irrigation technology in place. The implementation of consumptive use on trade does not insure third party or environmental interests. In fact, a farmer who improves the on-farm irrigation technology will reduce the return flow and benefit from more water use at the detriment of downstream users (Brennan and Scoccimarro, 1999). The farmer may also benefit from a public subsidy to improve the on-farm technology. Thus, contradictory signals are given to farmers since the constraint comsumptive use imposes on water trading gives an implicit right to downstream water users to return flows while the subsidy of irrigation technology fails to give any recognition to these users. The consumptive use constraint is a public intervention on a market system through regulation. Its aim is to protect third parties as well as the environmental interests. In addition, it is argued that the non-imposition of such a constraint will result in an over allocation of the water resource in a river basin (Young and McColl, 2002).

Should LDC allocate water rights to the environment at the same time they implement water markets? Considering the environment prior to the allocation of water rights to private users has the advantage of avoiding the market failure that occurred in many areas that did not provide rights for the ecosystem such as Chile and Colorado (CBTP). However, it does not appear that the utility obtained from water uses in the environmental sector, in the LDC, outweigh the uses in other sectors. Food production, urban growth and industrial uses of water seem to be more highly valued by decision-makers at the current level of development in many LDCs. If the environmental effects are reversible, it would be preferable to ignore the environmental rights and allow income creation and growth as a first step of water market implementation. However, this approach will later pose a problem with the need to expropriate private water rights to protect the environment.

The increase in demand of urban water will not exceed 5% to 10% of total current water uses. A marginal change in agricultural water uses (5% to 10%) will not dramatically cause environmental damage, if these water transfers are dispersed and not concentrated on a single river basin with a well functioning water market these changes can happen smoothly and progressively. However, as income rises in the future, pressure on the government to take better care of the environment will likely increase. Only then will more water be transferred from the agricultural sector to the environmental sector.

Full compensation for water rights

In the case of diversion of water for environmental, health or other reasons full compensation should occur. This is the case in Chile and the USA. However, in Mexico diversion has occurred without full compensation, which resulted in less security of water rights. In South Africa no compensation is provided if rights are to be transferred for the environment or social uses. In Australia, the legislation varies across states but the general principles regarding compensation don't allow users any right to compensation.

Trade within and between sectors

For a water market to be active no restrictions should be imposed on the market entry and exit; that is transfers should be allowed within and between sectors. As the growth goes on in the LDC one expects demand to rise in the urban and industrial sector. The main objective of implementing water markets is then to respond to these future demands in an efficient and economic way.

Prior approval to trade

In Mexico, prior approval of transfers is needed in case the trade affects a third party. This is also the case in Australia, Texas and Chile. In Colorado, no prior approval of trade is required, but the buyer must be able to demonstrate a beneficial use of the water (Ford et al. 2001). In fact, in Colorado the market is based on a court system rather than a public water agency. The transfers must be advertised and third parties that perceive them to be injured have to use the water court. There is no recourse once the transfer is approved (Howe, 1998).

Contribution to O&M costs of WUA after transfer

One of the negative externalities of water transfers outside the irrigation area discussed in the literature involves higher O&M costs for the remaining farmers in the irrigation system (Easter and Smith, 2002). In order to prevent this problem, the WUAs in Mexico are imposing a fee to be paid for the operating and maintenance of the canal (Kloezen 1998). In Colorado, owners of the water rights pay a fixed fee per right.

Tax on water rights

In Chile, no property tax on water rights is imposed directly. However, the land tax does reflect the value of water since irrigated land does pay higher tax than non-irrigated land. No sales tax has been reported on water transfer.

CONCLUSIONS

Three types of water rights co-exist in the falaj system in Oman. These are private, common and quasi public rights. Water markets in Oman are active mainly in Daudi falaj and consist on lease of common and quasi public water rights. Lease of the common water shares provides a sustainable flow of income for falaj maintenance and administrative expenses. The lease of water rights together with the community based management structure of the falaj largely explain the perpetuation of the system over several centuries. Permanent transfer or lease of private water rights are less frequent. Water rights lease take place in a special market generally on a weekly basis under the supervision of the falaj manager. Falaj thus constitutes an excellent management system where water rights are in use for small holders. The enforcement of water rights is undertaken by the water users community and independently of state intervention.

Unfortunately, the seniority principle in falaj water rights is not correctly implemented. Although legislation stipulates that 3.5 km around the falaj's "motherwell" is a protection zone, few resources are dedicated to control these protected zones in practice. Consequently, several Aflaj went dry and the oases around them were completely lost just because new wells were dug by newly established private individuals in the protected zones. The survival of Aflaj thus depends heavily on the establishment of water quotas or water rights for groundwater uses including tube wells.

It has been observed that falaj water is exchanged mainly within a farmers' community and when infrastructure allows it is transferred to other communities for agricultural uses. However, no transfer is observed to urban uses. Even worse, in many falaj, people depend for domestic water on pumped groundwater (from the same aquifer) serviced by private water companies charging around 0.445 O.R/m3 while the value of exchanged water among farmers is around 0.008 O.R/m3 (Zekri and Al-Jabri, 2005). It is in the interest of Aflaj communities to integrate domestic water into falaj management in order to reduce the cost to community members and increase the returns for falaj maintenance and operations.

So far Oman has been relying on both groundwater pumping and desalination for domestic purposes. However, during the last decade there has been a tendency to rely more on desalination rather than groundwater, as in the other Gulf Countries. The existence of water rights over 38 % of groundwater managed through Aflaj represents an excellent opportunity to establish a full market in tradable water rights, as an alternative to the exclusive market among farmers. Opening up the water market certainly requires a closer evaluation of such transfer possibilities and their economic and environmental impacts. The water legislations in other countries takes into account the impacts on third parties when water is transferred to other uses or regions. However, in the case of Oman, the water traded is a flow of groundwater with little impact on third parties. The main environmental impact that should be carefully considered is the landscape change which affects the sellers in the first place and other community members as a negative externality.

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Water Management for Kuwait In the 21st Century

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WATER MANAGEMENT FOR KUWAIT IN THE 21ST CENTURY

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ABSTRACT

Water management will be one of the most challenging problems in the 21st century. Almost all the countries around the world irrespective of their financial standing will feel the problem. The reasons for this are: increasing population, demands for higher water quality, declining fresh water resources, and increased cost of production of high quality water. Established ideas regarding water management should change to overcome and solve the above problem. Any change in water management policy should be gradual and it should be implemented over a long period of time. The policy proposed here is based on the principle that water quality and water usage should be linked. In other words, potable water, which is of very high quality, should not be used for other purposes like toilet flushing, showering and gardening. By implementing this policy, water production costs can be reduced considerably. This policy also implies to the reuse of wastewater at various stages. Kuwait's high standard of living is reflected in its high water usage. In 2004, freshwater usage was about 1059 Mega liters per day and brackish water usage was about 277 Mega liters per day. This is one of the highest usages in the world. To meet this demand, Kuwait's desalination plant capacity in the year 2004 was 1063 Mega liters per day for producing fresh water, brackish water is pumped out of the ground. Without any major change in the water policy, fresh and brackish water demand in the year 2050 will be ten times that in 2004. This will result in an enormous financial burden on Kuwait's economy and a severe decline in groundwater levels. By implementing the proposed policy, fresh water and brackish water production in the year 2050 could be pegged at 2004 levels with increased water recycling.

Keywords: water demand, water quality, domestic use, recycling.

Introduction

Water management will be one of the major challenges of the 21st century. Until recently, water management was a reasonably simple process in most countries. Freshwater was collected from various sources like lakes, reservoirs, aquifers, etc., and pumped to a central treatment plant for treatment. The treated water was distributed to the consumers through a network of pipelines. The ultimate source of fresh water is rainfall. When rainfall falls below the average levels, availability of freshwater is a major problem forcing water supply authorities to look for alternative modes of supply of water. In many cases, the consumers are subjected to severe hardship because of the erratic supply. In recent years, many countries faced erratic rainfall probably caused by Greenhouse effects forcing them to revise their established ideas about water supply management. In the year 2004, Sydney, Australia, a water rich city, suffered one of the major water shortages it ever had when its storage levels dropped below 40%. Sydney introduced severe water restrictions and developed plans for the construction of major seawater desalination plants at a cost of about 600 Million Dollars. Desalination plants are considered to be the ultimate solution for the shortage or lack of fresh water but they are very expensive and are well beyond the reach of many countries. Alternatively, water management plans could be revised to make efficient use of available freshwater and thereby avoid or postpone the need for desalination plants.

The present paper examines one such alternative management plan for the supply of freshwater. Kuwait is taken as a case study because of its scarcity of freshwater and its heavy reliance on seawater desalination. Kuwait is an affluent country with considerable oil reserves. Water management at present is not posing any major problems. As the demand increases, more and more desalination plants are constructed without causing any major financial hardship. However, in the 21st century, as the demand grows and oil becomes scarce, construction of additional desalination plants might place an enormous burden on the economy of the country. In the present paper, water management in the year 2050 is examined as compared to that in 2004. The results are useful to other countries with or without large oil reserves.

Water Supply in Kuwait

Kuwait is an oil rich nation with a per capita income of about 3,672 Kuwaiti Dinars [1] (1987 figures). One Kuwaiti Dinar equals US $3.00 approximately. Fresh water sources are non-existent except for a small aquifer in northern Kuwait. Fresh water from this aquifer is used for producing bottled water. Groundwater in most of Kuwait is either brackish or saltwater. Brackish groundwater with total dissolved solids (TDS) less than 5000 parts per million (PPM) is used for gardening and external water uses like cleaning, etc. Freshwater for all other purposes is produced by distillation. This water has a TDS less than 500 PPM. Kuwait has a dual pipeline system; one for the brackish groundwater, and the other for desalinated water. Recently, declining groundwater levels has forced the Ministry of Water and Electricity to restrict the supply of groundwater [2]. Table 1 shows the consumption of freshwater and brackish water since 1970.

Table 2 compares water consumption in different cities within the Gulf region [3]. In 1980, water consumption for different cities was of a similar magnitude. However, in 2004, total water consumption for Kuwait has gone up to 1336 Mega liters per day (ML/D). This is about 740 Liters per capita per day (L/C/D). This is one of the highest water consumption figures recorded anywhere. There are several reasons for high water demand [4]. Factors that affect water demand are: climate, water use habits of people, city size, cost of water, increasing industrial water demand, supply pressure, water quality, level of sanitation, and system of supply (continuous and intermittent). Another factor that contributes to the high consumption is the leakage. Leakage of water exists practically in every system [5]. Leakage could vary from 15% to 50 %.

Kuwait, though relatively affluent, could face severe problems in the future if its water management principles are not revised. This is the case with almost all countries around the world today.

Table 1: Water consumption in Kuwait (1970-2004)

Year	Population (Million)	Fresh water consumption (ML/D)	Brackish water consumption (ML/D)	Total water consumption (ML/D)	Per capita consumption (L/C/D)
1970	0.72	82	67	149	207
1975	1.04	144	98	242	233
1980	1.4	291	122	401	295
1985	1.8	460	161	621	345
1990	2.1	592	147	739	352
1995	1.7	767	199	966	568
1997	1.8	913	239	1152	640
2004	2.09	1059	277	1336	640

Table 2: Per capita water consumption in various cities (2000 figures).

City	Consumption L/C/D
Kuwait	401
Dammam	300
Muscat	300
Cairo	575
Baghdad	350
Bahrain	275

Table 3: Per capita consumption vs. population.

Population	L/C/D consumption
5000	15
10,000	25
20.000	45
50,000	70
200,000	115
>200,000	205

Table 4: Domestic water consumption.

Function	Per capita Consumption L/C/D
Bathing	55
Washing clothes	20
Toilet flushing	30
Dishwashing	20
Cooking and Drinking	10

Water Management

Water management until now in most countries means supplying the demand with optimum allocation of water resources. Whenever demand increases, existing supplies are increased or alternative supplies are found. Such a strategy cannot be pursued forever because of the high cost of water and associated environmental problems. Hence, water management principles must be revised to meet the increased demands of water with available resources. There are two ways of achieving this objective. One is to restrict the water demand by water conservation principles without affecting the living life style. Second is to link water usage to the level of water quality. In other words, potable water should never be used for other purposes such as gardening, toilet flushing, cleaning, etc. Water usage other than drinking and cooking could well be supplied with much inferior water quality. Inferior water quality mostly comes from brackish water aquifers and recycled water. The present paper examines various scenarios with respect to Kuwait's water demand in the year 2050.

Options Available for Water Management

Water management principles cannot be revised unilaterally. Public acceptance plays a major role in water management. Any changes in water management should be gradual and taken over a long period of time. In the present example, a total of five options were considered for water management in Kuwait in the year 2050.

Option 1: (Present Operating Conditions)

This option assumes no change in the present water management policy. If the population grows at the present level and per capita water demand for fresh water and brackish water increase at 2004 levels then, Table 5 presents water demand levels in 2050. Increasing population increases per capita water consumption as shown in Table 3. One of the reasons for this trend is that as population increases the area of the pipe network increases resulting in higher losses and leakage. Population in Kuwait is a mixture of Kuwaitis and non-Kuwaitis. Growth of the Kuwaiti population can be predicted with a reasonable degree of confidence. The rate of growth of non –Kuwaitis is rather difficult to predict. In the late 80s, Kuwaiti population was 40% of the total population [1]. In the present analysis, total population in the year 2004 was extrapolated to get 2050 figures.

Table 5 also presents figures for the years 1970 and 2004 for the sake of comparison. In the year 2050, desalination plant capacity will be ten times that in the year 2004. Brackish water demand is high and aquifers will not be able to meet this high demand. This will place even higher demands on the desalination plant capacities. This scenario is totally unacceptable even for an affluent country like Kuwait. Hence, alternatives must be found and pursued.

Option 2: (Implementation of Water Conservation Schemes)

This option is relatively easy to follow. This assumes that per capita consumption of fresh water and brackish water should be restricted and limited at 2004 levels. This would require implementation of water conservation methods and mild restrictions if necessary. Table 5 shows the water demands for this option in the year 2050. With Option 2, desalination plant capacity required in 2050 will be about half that is required under Option 1. This represents a substantial saving.

Option 3: (Restriction of Groundwater Use)

In Option 2, per capita brackish water demand was pegged at 2004 levels. Even with this restriction total brackish water required is high and the present aquifers might not be in apposition to meet such demands. Hence, in Option 3, the total brackish water supply is limited to 2004 levels and the short fall in brackish water supply will be met by desalinated water. Hence, in Option 3 desalination plant capacity required is higher than that in Option 2. However, this is more realistic because of the limitations of the present aquifers in Kuwait.

Option 4: (Restricted Water Use)

This option will be difficult to implement in the present time frame because the public is used to high water usage habits. But in years to come, the water supply authority might not have any other choice but to implement such drastic measures. In this option, water demand is limited to actual use. Table 4 lists per capita domestic water requirements for different functions [6]. Cooking and drinking requires only 10 L/C/D. Hence, high quality water required is only 10 L/C/D. All other usages can manage with water of lesser quality. In this option, per capita fresh water consumption is limited to 135 L/C/D. Brackish water consumption is limited to 50 L/C/D. Such low usage levels can be achieved by severely restricting the water supply and /or raising the price of water to realistic levels. This option results in substantial savings in the installation and operating costs of desalination plants [7]. The desalination plant capacity required under this option will be same as that in 2004 levels.

Table 5: Water demand projections for Kuwait (options 1-5) for the year 2050.

	1970	2004	2050				
			Option 1	Option 2	Option 3	Option 4	Option 5
Population (Million)	0.72	2.09	6.8	6.8	6.8	6.8	6.8
Per capita fresh water (L/C/D)	114	640	1278	507	507	135	105
Total freshwater (ML/D)	82	1059	8690	3447	4112	918	714
Per capita brackish water (L/C//D)	93	133	212	133	133	50	27
Total brackish water (ML/D)	67	277	1441	904	239	340	184
Per capita recycled water (L/C/D)	0	0	0	0	0	0	53
Total recycled water (ML/D)	0	0	0	0	0	0	360
Total water (ML/D)	149	1336	10,131	4351	4351	1258	1258
Desalination plant capacity (ML/D)	123	1063	10,428	4136	4934	1102	857

Option 5: (Use of Poor Quality Water for Non-potable Uses)

This option is an extension of Option 4. In this option, water recycling is introduced. Recycled water is used for toilet flushing and external garden use. Per capita brackish water use is limited to 27 L/C/D and per capita recycled water will be 53 L/C/D. This option will be the likely option in the year 2050. Under this option, desalination plant capacity required in the year 2050 will be less than that in 2004 and total brackish ground water pumped out of the ground will also be less than that in 2004.

Implementation of Policies

Options 2 to 5 require implementation strategies considering the nature and status of the public. The implementation should be gradual otherwise a severe backlash could be expected from the public. For example, in today's conditions, use of recycled water could be totally unacceptable. However, the public should be made aware of the fact that high water usage requires high capital outlay and the funds for such a scenario should be ultimately come from the public.

Conclusions

Water management will be one of the most challenging problems in the 21st century. Almost all the countries around the world irrespective of their financial standing will feel the problem.

Established ideas regarding water management should change to overcome and solve the above problem. Any change in water management policy should be gradual and it should be implemented over a long period of time. The policy shift proposed here is based on the principle that water quality and water usage should be linked. In other words, potable water, which is of very high quality, should not be used for other purposes like toilet flushing, showering and gardening. By implementing this policy, water production costs can be reduced considerably. This policy also implies the reuse of wastewater at various stages.

Kuwait's high standard of living is reflected in its high water usage. In 2004, freshwater usage was about 1059 Mega liters per day and brackish water usage was about 277 Mega liters per day. This is one of the highest in the world. To meet this demand, Kuwait's desalination plant capacity in the year 2004 was 1063 Mega liters per day for producing fresh water, and the brackish water is pumped out of ground. Without any major change in the water policy, fresh and brackish water demand in the year 2050 will be ten times that in 2004. This will result in an enormous financial burden on Kuwait's economy and a severe decline in groundwater levels. By implementing the proposed policy, fresh water and brackish water production in the year 2050 could be pegged at 2004 levels with increased water recycling.

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Integrated Water Resources Management
The United Nations Water Virtual Learning Center

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ABSTRACT

The UN Millennium Development Goals (2000) and the World Summit on Sustainable Development (Johannesburg, 2002) pledged to halve the proportion of people without access to safe drinking water and basic sanitation by 2015. To achieve these targets, an additional 1.5 billion people will require improved access to water supply. This means providing services for another 100 million people each year (274,000/day) between 2000 and 2015. To meet the MDGs, we have to train the personnel required to design, manage and operate all of the affected water systems to serve these 100 million people per year. This includes all the people involved in building and operating water treatment plants, wastewater treatment plants, distribution systems, groundwater wells, as well as the people responsible for water testing, monitoring, regulation and remediation; and all the people involved in water source protection, environmental monitoring and remediation, cleanup of contaminated water, etc. If we are to meet the MDGs by 2015, we must assist the current generation of managers, scientists and policy makers to improve water management practices and will need a focus on adult education. The Water Virtual Learning Center is specifically designed to train water professionals in IWRM. UNU-INWEH has joined with the UN-Department of Economic and Social Affairs to develop the WVLC as an Internet- and CDROM-based, regionally delivered system. UNU-INWEH has designed and developed the curriculum on IWRM, together with the supporting information technology system. Its long-term goal is to enhance national capacities for the development and implementation of sustainable water strategies at local, regional, sub-regional and basin scales. The curriculum offers broad-based coverage of the principles and practices of IWRM, providing the students with core knowledge in the natural sciences, engineering, health, governance, public administration, social sciences, economics, resource conservation, strategic planning, as well as aspects of program and project management. Upon successful completion of the program, the participants will receive a United Nations University Diploma in Integrated Water Resource Management

Introduction

The Millenium Development Goals

Water is essential for human beings to survive and develop. At the same time water is a scarce resource, sometimes the shortage is so acute it causes crises. Both facts lead to the simple conclusion that lack of water hinders development and the right to live in dignity. At the beginning of 2000, an estimated 1.1 billion people (one sixth) of the world's population were without access to safe water and 2.4 billion people (two-fifths) lacked access to improved sanitation. Over 6,000 people, mainly children, die each day from drinking water related diseases, mainly diarrhea, caused by unsafe water, poor sanitation and poor hygiene practices. This equates to over 2.2 million people dying each year[1]. Approximately 4 billion cases of diarrhea each year cause 2.2 million deaths, mostly among children under the age of five. This is equivalent to one child dying every 15 seconds, or 20 jumbo jets crashing every day[2].

The United Nations Millennium Development Goals (MDGs)[3] and the results of the World Summit on Sustainable Development (Johannesburg, 2002) pledge to halve the number of people in the world without access to safe drinking water and basic sanitation by 2015. To achieve these targets an additional 1.5 billion people (100 million per year, 274,000 per day) will require access to a safe water supply during that period. If we are to achieve the goals, there is another aspect of sustainability that has to be considered. This is the requirement to provide the capacity to deploy and maintain all of the infrastructure, economic mechanisms, legal, social and community frameworks necessary to sustain the progress achieved and to go further and provide safe water to the remaining unserved populations. Similar problems are present with providing basic sanitation.

To help meet these challenges, the UN Water Virtual Learning Center, cooperation between UN-Department of Economic and Social Affairs and United Nations University – International Network on Water, Environment and Health was developed. It is designed to teach practitioners in the water sector the principles of Integrated Water Resource Management and so assist in the implementation of safe drinking water and sanitation in developing countries.

Integrated Water Resource Management

Integrated Water Resource Management (IWRM) is a simple concept with exceedingly complex implications for water professionals around the world. It has been defined as "a process, which promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (Global Water Partnership - Technical Advisory Committee, 2000). It is goal-oriented and seeks "to develop a consensus-based vision of ideal water resources conditions for the area of interest".

Figure 1 provides a large-scale overview of the processes, agencies or institutions that can be involved in an IWRM plan.

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[1] http://www.wsscc.org/download/Resource_Pack_on_MDGs.pdf

[2] http://www.who.int/docstore/water_sanitation_health/Globassessment/Global1.htm

[3] United Nations Millennium Declaration, General Assembly Resolution 55/2 of September 8, 2000, U.N.Doc. A/RES/55/2

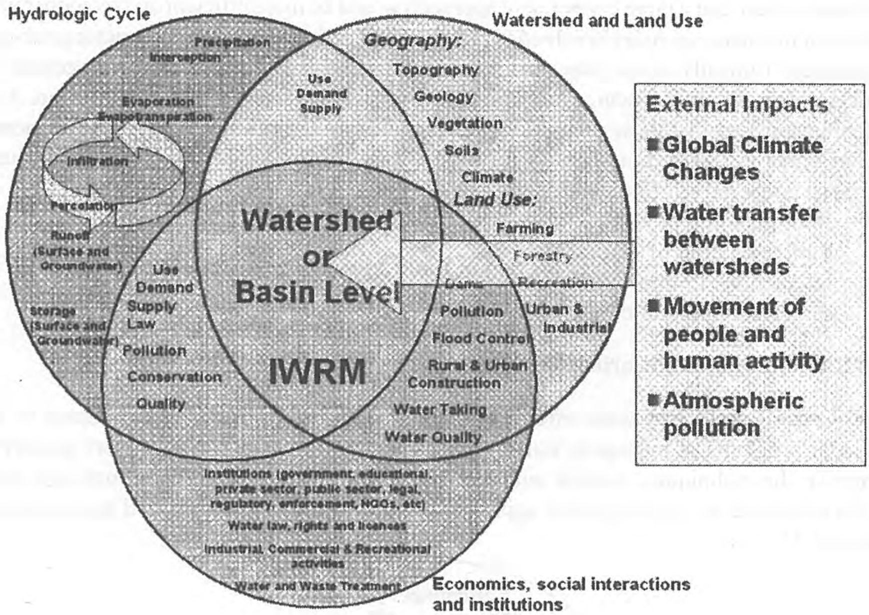

Figure 1: Overview of Integrated Water Resource Management

An IWRM plan should involve aspects of the hydrologic cycle, land use, climate, geography and pollution, economics, social interactions and institutional aspects relating to IWRM. It should also deal with the issues of water taking, quality, conservation and legislation, monitoring and regulation, as well as the physical aspects of flood control, dams and water and wastewater treatment engineering works. The confluence of all of these aspects, usually at a river basin or watershed level, is central to the practice of effective IWRM. Of course, there are many external impacts on IWRM such as the effects of global climate change, water transfer between watersheds, movement of populations and the consequent changes in human activities and the effect of atmospheric transfer of pollutants – sometimes occurring on a continental or even global scale.

The history of IWRM can be traced back to historic times and the various stages are:

The Sectoral Approach (Historic to 1950s)

Each sector involved in water and wastewater issues did its own planning and implementation except when the various sectors had overlapping responsibilities. There were therefore separate:

- Planning and implementation processes
- Activities and tasks (such as water storage, transmission, distribution, allocation)
- Physical and construction measures (water canals, dams, reservoirs)
- Legal and economic instruments such as regulations and incentives
- Institutional and organizational requirements

The Cooperative Approach (1960s and 1970s)

It became clear that a more cooperative approach would be more efficient and so cooperation between the many agencies involved in planning and activities in the water sector gradually improved. Typically, some joint planning and activities between two or more agencies or stakeholders started to occur, even where their legal responsibilities did not overlap. As it became apparent that these plans, activities, regulatory activities, and legal and economic frameworks intersected, ad-hoc cooperative efforts became more common. The features of these cooperative efforts were:

- Joint planning processes for two or more agencies or stakeholders
- Rationalization of certain activities
- Interactions to improve regulatory and economic frameworks
- Better institutional cooperation

IWRM - Management-oriented (1980s)

Early efforts at IWRM were often based on an extension of ecosystem science to the broader problems of managing water supplies. The goals of such efforts were usually to improve the techniques, models and data sources for such integration efforts and were often presented as "an integrative approach to water resource or watershed management" (Figure 2)

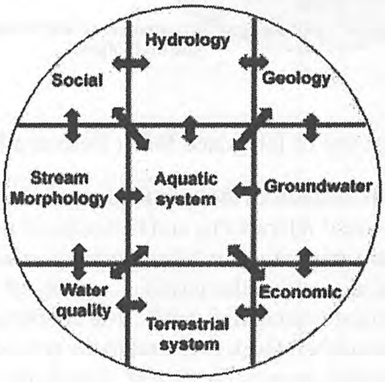

Figure 2: Management-oriented IWRM

There are many examples of such early attempts at IWRM. Some recommendations for Canadian policies were developed by Pearse et al (1985). The "key" principles were:

- A watershed plan sufficiently comprehensive to take into account all uses of the water system and other activities that affect water flow and quality.
- Information about the watershed's full hydrological regime.
- An analytical system, or model, capable of revealing the full range of impacts that would be produced by particular uses and developments in the watershed
- Specified management objectives for the watershed, with criteria for assessing management alternatives in an objective and unbiased way
- Participation of all relevant regulatory agencies
- Provisions for public participation in determining objectives and in management decisions

A typical hydrologic model would describe the flows through the system and permit scenario-modelling or aid in managing the resource (Figure 3);

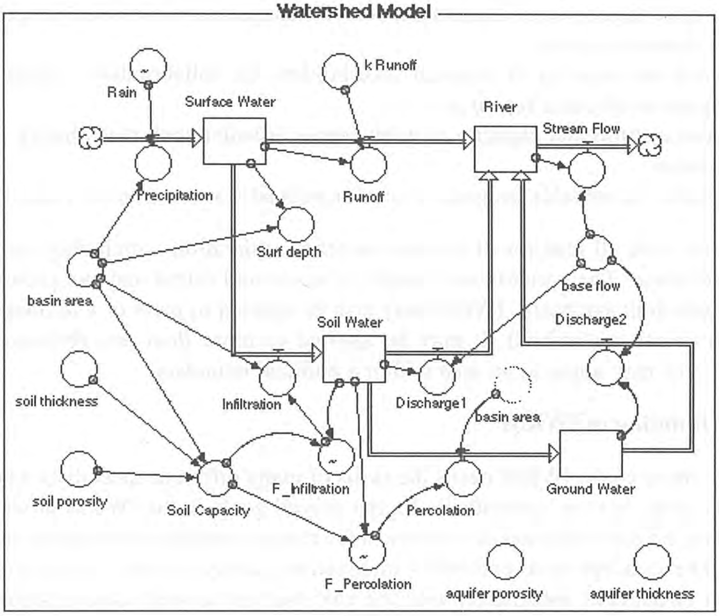

Figure 3: Typical hydrologic model of a watershed (http://www.acad.carleton.edu/curricular/GEOL/DaveSTELLA/Water/watershed/2.gif) from "Modeling Water flow in a Watershed"

Such efforts led to the development of excellent hydrologic models of rivers, lakes and watersheds but were usually performed by a few agencies, often working together, and, initially at least, had very little input from the wider range of water users and other stakeholders. Gradually more and more input from these groups was sought and the process of IWRM changed from a management-oriented one to one that was much more goal-oriented.

IWRM - Goal-oriented (1990s to today)

If IWRM is defined as "a process which promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (Global Water Partnership – Technical Advisory Committee, 2000), then the focus shifts.

The goals become the most important focus;

- To develop a consensus-based vision of ideal water resources conditions for the area of interest.
- To measure the distance between current and ideal conditions, and thus define one or more water management problems, based on consensus among stakeholders.
- To develop and apply tools for water resources decision making, including demonstration projects, computer simulation models, conflict resolution tools, data management and sharing, and so on.

- To identify appropriate management actions to resolve observed problems.
- To assign responsibility for actions and costs for remedial measures.
- To agree upon acceptable timelines for implementation of management actions.
- To monitor the degree of implementation of management actions and progress toward water resources goals.
- To build the capacity of regional stakeholders for collaborative, consensus-based management of water resources.
- To build institutional capacity to work across jurisdictional, disciplinary, and sector boundaries.
- To achieve measurable progress toward improved water resources conditions

IWRM deals with all features of the area under consideration – including surface water and ground water. The groundwater aquifer structure and extent may not correspond to a surface water drainage basin. IWRM may also be applied to parts of a drainage basin or watershed (a sub-watershed). It may be applied to more than one drainage basin or watershed – or may apply to an area within a political boundary.

Capacity Building in IWRM

To achieve these goals, IWRM needs the skills of many different specialists who may not be familiar with, or even sympathetic to, the overall goals in the IWRM process IWRM has gone beyond the traditional description of the resource and then integrating or balancing demand. The concept now embodies integration across sectors, integration of use, integration of demand, integration with the environment as well as integration with the people.

From the perspective of CAPNet, (an international network for capacity building on integrated water resources management - http://www.cap-net.org/) "IWRM means a shift from development focus to management focus. It also means recognizing that there are many competing interests in how water is used and allocated and these various stakeholders should be active participants in water management. The traditional sectoral top down role of water professionals is being challenged and the demand is for integration - between sectors, between users, and equally importantly across the different components of the water cycle. Groundwater, surface water, upstream, downstream, green water and blue water are all inextricably linked and management of the water resource must take this into account. Traditional water professional skills and knowledge continue to be essential, and may even be strengthened by the introduction of IWRM, but they are not enough. There is an urgent need for additional skills in management, institutional reform, conflict resolution, social and communication skills in the existing and new water managers".

Any education or training program in IWRM must attempt to convey these essential features to a diverse group of professionals and to all community members and water users. These professionals can come from many different backgrounds in engineering, biology, chemistry, microbiology, soil science, climatology, hydrology, hydrogeology, remote sensing, geographic information systems, cartography, computer science, modeling and simulation, management sciences, agriculture, sociology, ecology, economics, aquatic toxicology, environmental sciences, legal and regulatory areas, and political science.

It is a common conclusion that success in IWRM comes from an integration process that has the following general characteristics:

- All participants agree to and share a common set of goals for the study area. These are defined in advance and modified as required.
- Information and data are accessible and provided to all participants.
- There is a well-understood "core" of basic information, shared by all, about all aspects of the study area.
- Capacity building is targeted towards ensuring that all participants share a common set of basic knowledge, data and capabilities, especially in areas where they are not specialists.
- Genuine participatory decision making is the rule, not the exception.
- Conflict resolution procedures are available and used.
- Reporting is a collaborative process.
- Management and implementation are also collaborative

Combining the variety of skills required for successful IWRM projects with the conditions for success listed above, it is clear that a new scheme for training and educating the participants in an IWRM exercise would greatly assist the development and application of IWRM principles. This new schema should address the problems inherent in meeting the "conditions for success"; common goals, availability of data and information, a "core" set of shared information, methods for participatory decision making, and the use of conflict resolution, collaborative reporting and collaborative management. Any capacity building exercises should address these areas of concern to ensure that all participants in IWRM have these shared values, information, goals and methodologies. This necessarily implies that they should all have a common training and education program about aspects of IWRM that are generally agreed to be central to the successful outcome of IWRM projects.

The UN Water Virtual Learning Centre is specifically designed to answer this need; it is also targeted at practicing water professionals or others associated with IWRM practice and were designed for delivery by Distance Learning via CDROM or the Internet.

The UN-WVLC

Certain principles have been assumed for the WVLC:

- There is a common "core" knowledge base that all participants in an IWRM exercise can share.
- This knowledge base can be communicated to all participants.
- When capacity building is completed, the participants interact more effectively and the dialog on the IWRM process also becomes more effective.

Curriculum Design

The curriculum design process was intended to assess those topics that should be familiar to practitioners in any specialty working in an IWRM project. The process followed was one of iterative design; an initial curriculum based on a survey of IWRM practices and courses around the world was developed, submitted to international specialists in IWRM and modified according to their comments and suggestions. After some iterations of this process, an agreed core curriculum was finalized (Mayfield, et al).

The result of this process was the definition of a series of courses that together covered the required subject areas.
Course 1: An Introduction to IWRM

Course 2 - Water Transfer
Course 3 - The Terrestrial Ecosystem and the Impacts of Land Use Changes
Course 4 - The Aquatic Ecosystem and the Impacts of Land Use Changes
Course 5 - Aquatic Ecosystem Health and Impact Assessment
Course 6 - Water Use
Course 7 - Waste Water
Course 8 - Governance and Community- Based Approaches
Course 9 - Organizational Infrastructure and Management
Course 10 - Applying Integrated Water Resources Management

As an example of the design process, Course 2 – Water Transfer was first defined as a series of goals:

Goals: The participants shall examine and understand:

- The mechanisms of the hydrologic cycle; how water moves through the cycle.
- The important processes of the cycle in the atmosphere, the land, rivers, streams and lakes.
- Basic hydrological concepts such as climate change, erosion, infiltration, run-off, stream flow, base flow, water storage, riparian functions, water budgets and modeling in surface and groundwater.
- Simple measurement techniques in hydrology

These were translated to a series of topics:

- Water and the Atmosphere
- Water and Land
- Water and the Riparian Environment
- Water and Lakes
- Water Budgets

The course materials were then assembled by an editor from a database of relevant materials. The items in the database were taken from other courses and publications by the government, the private sector and international agencies and were classified by author, title and a set of keywords describing the contents and their possible application to each of the courses. Copyright releases were obtained where necessary from the authors or publishers of the documents.

Final editing of all courses was carried out to ensure consistency, correct English usage and standard terminology (as far as possible). All of the course materials were then converted to standard HTML files for assembly into individual courses.

Study Space™ learning environment software

The requirement that the software for course delivery should be able to deliver the courses on CDROM, over the Internet or through printed versions, and that these should be as similar as possible led to the adoption of the Study Space™ learning environment. This software was initially developed at the University of Waterloo, Ontario, Canada by the Computer Systems Group and was significantly modified and tailored for use in the WVLC.

Assembly of course materials can be from word processing files, Microsoft PowerPoint slides, HTML pages or any other source (video, audio, animations, vector graphics, Flash media, etc) that can be displayed in a modern browser such as Microsoft Explorer Version 6. The course structure is designed to resemble a standard lecture format as closely as possible.

Each set of pages equivalent to a lecture consists of a series of pairs of "concept" and "discussion" pages. These can be regarded as functionally identical to the PowerPoint slide and the surrounding discussion used in the standard lecture format.

Each of these sets of concept and discussion pages are then linked and the order of presentation specified in an XML - based course structure file that simply lists the pages and determines whether they are included in the overall menu for the course. Headings for course sections and subheadings within those sections are also specified in the XML course structure file. This very flexible arrangement means that the entire course layout, menu structure and appearance can be modified by simply changing the XML course structure file; no internal or external links between pages are required. Since templates are provided, no computer programming skills are required to produce or edit this XML course structure file.

From the users point of view, navigation through the course materials is done by switching between the "concept" and "discussion" page for each lecture topic, by using the "Next" and "Previous" page buttons on the menu at the top of the page, or by going directly to the drop-down main menu items in the left-hand pane of the browser (Figure 4).

Figure 4: Navigation bar

The software also keeps track on the users computer which pages (both concept and discussion) the user has visited and also allows the user to indicate for each page his or her "level of understanding". This is accomplished by adjusting a sliding bar at the top of the page that allows to the user to designate low, medium or high levels of understanding of the topic. The user at any time can retrieve the history of visited pages (Figure 5) and the outline of their designated level of understanding of each topic (Figure 6).

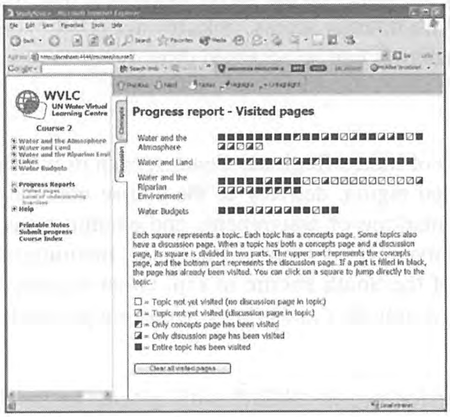

Figure 5: Visited pages overview

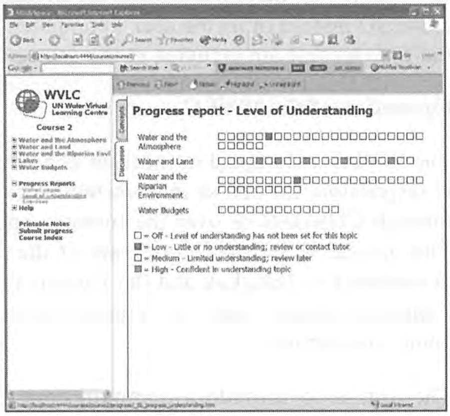

Figure 6: Level of understanding overview

Other features of the software are the ability to selectively print sections of the course or the entire course, a Notes facility that allows the user to make margin notes and a Highlighting facility that allows the user to highlight important points in the text. Both the Notes and Highlighting are stored attached to the particular topic page (Figure 7).

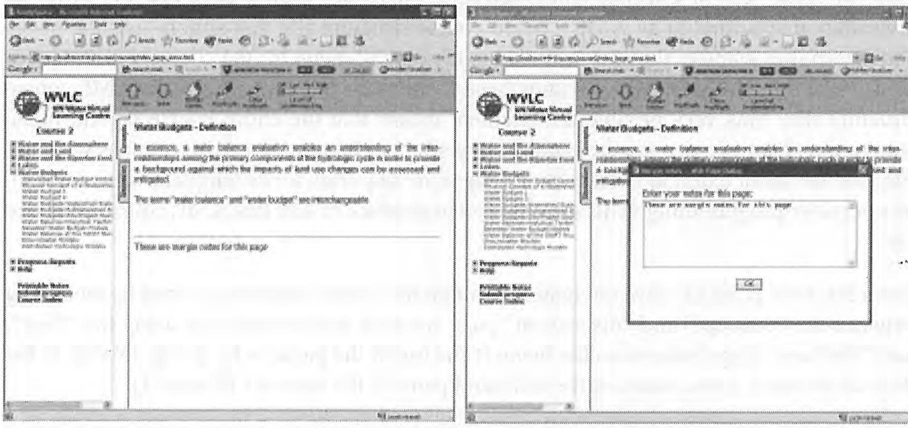

Figure 7: Margin Notes in Study Space

As a tracking mechanism the user can opt to send a report to a central server that provides details on the users progress through the course, which pages have been visited (and when) and also sends their self-assigned level of understanding of each topic. This can be done over an Internet connection if available, via a file attached to an email or through a printout sent by mail. This is designed to allow the course designers to discover and correct problems associated with any particular topic or with the users progress through the course materials.

Each of these functions is also replicated exactly on the Internet version of the courses. If a user has good access to the Internet, he or she can use the course materials in an identical manner; the only difference is that the data on use, progress through the course, level of understanding, margin notes, and highlighting are stored on the server associated with the a user ID instead of on the user's computer. With Internet access, links to sites (URLs) on the Internet that are included in the course materials can be accessed directly.

Operation of the WVLC

The WVLC is designed to function as a series of linked Regional Centers, each of which is responsible for course customization for that region, delivery of the course materials through CDROMs or over the Internet, and marking of assignments and examinations. The present Regional Centres are at the University of Ghana, the Asian Institute of Technology in Bangkok and the University of the South Pacific in Fiji. Other Regional Centers for South America, Central America, South Asia and other regions are presently being investigated.

The aim is to provide a common core curriculum in IWRM with extensive local customization to reflect regional priorities and conditions. To assist in that process, a workshop has already been held where the participants and coordinators from the present

Regional Centres were introduced to the course materials and the Study Space software. Details of course production, editing and modification were also covered.

The WVLC Program

The complete IWRM program in the WVLC consists of 10 courses; the first one is an introductory course and the final one is a practical course where the participants will produce a "skeleton" IWRM plan for their home region. The other courses deal with different areas important in IWRM from the point of view of a non-specialist in those areas. The curriculum development process was designed to extract those topics that practitioners in IWRM thought were important for all participants in an IWRM exercise to know. The program is not designed to produce an "IWRM specialist" – it is specifically designed to improve the communication and interaction between existing specialists in the many areas important in IWRM processes.

Upon successful completion of each course, the participants will be given a Certificate of Completion for that course. Upon completion of the entire program of 10 courses, including an examination taken during the final course, the participants will be granted a United Nations University Diploma in IWRM.

Discussion

If we are to meet the MDGs by 2015, we must assist the current generation of managers, scientists and policy makers to improve water management practices and will need a focus on adult education. Thus the target group for training is the practicing professionals in the water sector wishing to upgrade their knowledge of integrated water management. The program is offered via self-directed distance learning, so professionals would continue working while enhancing their skills in IWRM theory and practice. Its long-term goal is to enhance national capacities for the development and implementation of sustainable water strategies at local, regional, sub-regional and basin scales. The program uses a distance education learning approach for enhancing the skills of water professionals. The key outcome would be better skilled and trained water professionals with knowledge of integrated water resource management principles, methods and techniques.

The pilot scale implementation in the Regional Centers is intended to verify the suitability and relevance of the course material, gauge the reaction of the students to the program and discover any issues with the course delivery systems and the Study Space software. After this pilot phase the program can then be made more widely available.

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Evaluation of Water Management in Bahrain – A Case Study

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EVALUATION OF WATER MANAGEMENT IN BAHRAIN A CASE STUDY

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ABSTRACT

Bahrain has no surface water resources and its climate is arid. Until the mid 70s of the last century, groundwater was the only source of fresh water for municipal and agricultural use. The annual natural recharge to the main fresh water aquifer (Khobar) was estimated between 90 and 112 Mm^3 per year. Abstraction exceeded the recharge rate for the first time in the mid- 60s. The late 60s and early 70s experienced a sharp increase in abstraction for municipal use. Agricultural demand also increased sharply during the 60s. Abstraction beyond the safe yield caused lowering of the piezometric levels of the Khobar aquifer leading to salt water intrusion and salinisation. It was clear that Bahrain was facing a water resources crisis and some urgent measures were needed to avoid further groundwater depletion and salinisation. Measures to control abstraction for municipal use included building desalination plants to meet the rapidly growing municipal demand, maintaining acceptable tap water quality and protecting groundwater from depletion and salt water intrusion. Currently there are four desalination plants with a total design capacity of about 0.34 Mm^3 per day (75 MIGPD). It was planned that by the year 2006, production from the Hidd Power and Water Station (HPWS) alone will reach 0.41 Mm^3 per day (90 MIGPD). The Ministry of Electricity and Water also established the Water Conservation Department to minimize consumption and the Leak Detection Department to minimize losses from the transmission and distribution networks. Two Ameeri Decrees and a set of Executive Ministerial Orders were issued in the 80s and late 90s to set the legal framework to apply measures to control agricultural consumption. The proposed control measures included stopping drilling of new private wells, application of a consumption related tariff, installing recycling equipment on swimming pools, replacing crops of high consumption by others with low water requirements and improving irrigation practices. It was also planned to produce and utilize about 200,000 m^3 per day of Treated Sewage Effluent (TSE) for agriculture. It was expected that the above listed water management measures plus a number of others will reduce groundwater consumption by the year 2002 to about 107 Mm^3 per year and will result in reducing the Total Dissolved Solids (TDS) in tap water to about 600 mg/l. This paper extensively evaluates the various water management measures taken in Bahrain and their impact on demands and quality of groundwater and tap water. The study revealed that the above two targets are far from being achieved. The current annual groundwater abstraction is estimated at about 195 Mm^3 and the average tape water TDS is about 1400 mg/l. This is due to substantial delays in implementing the major projects such as upgrading HPWS, TSE production and application of the agricultural tariff. It is highly recommended that these projects are implemented soon in order to protect groundwater and improve tap water quality

Keywords: Bahrain, Groundwater, Municipal Water Consumption, Agricultural Water Consumption, Consumption Control, Demand Management

INTRODUCTION

Bahrain is an arid country with an average annual rainfall of about 80 mm and an evaporation rate estimated at about 3300 mm per year. Bahrain as such has no surface water resources. Until 1924, the people of Bahrain relied entirely on the natural discharge of a large number of land and marine fresh water springs and some shallow hand dug wells to meet their water requirements. Construction of deep wells began in 1925 and their numbers increased rapidly ever since. Khobar aquifer, with an estimated natural recharge between 90 to 112 Mm^3 per year [1, 2], was the main source of fresh groundwater to meet most of the community's water requirements. Following the discovery of oil in the thirties, the community in Bahrain experienced rapid growth in population, substantial improvements in living standards and later developed wasteful new water- using habits that led to a sharp increase in agricultural and municipal water demands. Fresh groundwater was over-exploited due to lack of understanding of the limited nature of this resource and its interaction with saline groundwater on one hand and sea water on the other. Decline in piezometric levels and increase in salinity were observed since 1940 [3]. By the mid 60s, abstraction from Khobar aquifer exceeded the natural recharge causing accelerated aquifer depletion and drop in the piezometric levels that led to excessive salt water intrusion from sea water and lower saline aquifers [4]. Nevertheless, groundwater continued to be the only source of fresh water to meet municipal and agricultural demands until the mid 70s. Continued over-abstraction of groundwater eventually led to a total loss of natural discharge from springs and salinisation of most of the Khobar aquifer by the end of last century (Figures 1, 2 and 3). Studies on water resources in Bahrain in the late 70s revealed the water resources crisis and the government was advised that sustainable use of groundwater is possible only if urgent measures are taken to limit abstraction to 90 Mm^3 per year [1]. The government's plans to solve the water resources crisis involved adopting measures to:

- Optimize Water Use and Minimize Waste and Losses
- Augment Groundwater by Nonconventional Water Resources.

This paper reviews and evaluates the measures adopted by the government to control groundwater abstraction. Since most of the groundwater was abstracted to meet agricultural and municipal demands, the efforts were concentrated on controlling consumption in those two sectors.

CONTROL OF AGRICULTURAL CONSUMPTION

Agricultural demand increased sharply from about 48 Mm^3 per year in 1952 [6] to about 96 Mm^3 per year in 1971[8]. Agricultural consumption continued to increase to reach a maximum of 180 Mm^3 per year in the late 90s [9]. Part of the increase in agricultural demand in the 60s and 70s can be attributed to the sharp increase in the irrigation rate which increased from about 1.5 m^3/m^2 in 1952 to around 5.2 m^3/m^2 in 1980 (Figure 4) indicating substantial waste and misuse. The Ameeri Decree of 1980 that was updated in 1997 and a number of related Ministerial Orders were issued to control agricultural consumption by:

- Installing Water Meters on all Wells and Applying Consumption Related Tariff.
- Installing Water Recycling Equipment on all Swimming Pools.
- Freezing Drilling of Private Wells.

An economically reasonable water tariff that is related to consumption is a very effective tool in controlling water consumption. Applying such a tariff can force the farmers to optimize their consumption by:

- Minimizing waste, misuse and losses
- Optimizing water use by using water conserving distribution methods and efficient irrigation practices and technologies
- Replacing high water consumption low value crops by others of high value and low water consumption.

In order to achieve the above, the Ministry of Agriculture began in 1980 installing meters on agricultural wells. Initially, there was some resistance but by 1984 the meters were eventually installed on most of the agricultural wells. A special tariff of 0.015 BD per m^3 was proposed for water used to grow alfalfa and 0.003 BD for all other crops. Alfalfa is one of the highest water consuming commonly grown fodder crops in Bahrain. The special 0.015 BD tariff was aimed at replacing alfalfa with crops having lower water requirements. Fearing the water bills, farmers began to replace some of their traditional water wasting irrigation practices by practices that were more efficient. This slightly reduced agricultural consumption in the mid 80s to around 3.5 m^3/m^2 (Figure 4). In addition, many of the swimming pools were refurbished and fitted with water recycling systems to reduce waste and misuse. Most of these pools were traditional in farms and offered for rent to the public on a daily basis throughout summer (May to October). The common practice to maintain fresh clean water in the pool in the presence of a large number of people was to keep pumping fresh groundwater to exchange the pool water throughout the day. Although the overflow is used for crop irrigation, it by far exceeds the needs of the plants and so substantial amounts of precious fresh groundwater was wasted.

The government's plans to reduce abstraction of groundwater for agricultural use also included expansion of the Tubli Water Pollution Control Centre (TWPCC) to be able to produce, by the year 2010, up to 200,000 m^3/day (H" 70 Mm^3 per year) of Treated Sewage Effluent (TSE) suitable for unrestricted use in farm land and landscape irrigation. The project also included the construction of extensive transmission and distribution networks and a large number of distribution reservoirs. The transmission and distribution network covers farms in the northern, western and central parts of Manama island and many parts of the main highways in the island. It was expected that this project would be completed in 2002 and around 60 Mm^3 per year of TSE would be produced and utilized by then, leading to a reduction in agricultural groundwater consumption by an equal amount.

CONTROL OF MUNICIPAL CONSUMPTION

Groundwater abstraction for municipal use in Bahrain increased from 5.1 Mm^3 per year in 1952 [6] to 59.7 Mm^3 per year in 1984 [9] representing a sustained annual increase of about 8%. Only part of the increase in demand can be attributed to growth in population since the latter is estimated at about 3.8% for the same period. Other causes of the sharp annual increase in demand include:

- Unjustified Increase in Per Capita Consumption (Figure 5,6)
- Substantial Losses from the Transmission and Distribution Networks (Figure 7)

A large proportion of the increase in per capita consumption can be attributed to leaks, waste and misuse. A number of measures were taken to control groundwater abstraction for municipal use including:

- Desalination of Saline Water as an Alternative Nonconventional Fresh Water Resource.
- Water Conservation and Minimization of Leaks, Waste and Misuse
- Leak Detection, Repair and Rehabilitation of the Water Transmission and Distribution networks
- Replacing the Old practice of 'Supply Management' by 'Demand Management'.
- Application of Metered Water Rates with a Step Increasing Tariff

Desalination of Salt Water

Desalination of salt water is part of the government's plans to provide alternative water resources. Another equally important objective for desalination is to improve the quality of municipal water. The first desalination unit was commissioned in 1975 with a production capacity of 0.011 Mm^3/d (2.5 Million Imperial Gallons per Day (MIGPD)). Today there are four desalination plants in operation with a total design capacity of 0.35 Mm^3/d (77.5 MIGPD) (Table 1). It was planned to expand the Hidd Power and Water Station (HPWS) to increase its production capacity to 0.41 Mm^3/d (90 MIGPD) by 2006.

Water Conservation

Changes in life style and improvements in living standards driven by increasing oil revenues especially in the late 60s and early 70s caused a substantial unjustified increase in per capita water consumption (Figure 6). Items such as bath tubs, large volume flush tanks, high water consumption fully automatic washing machines and pressure booster pumps in addition to house gardens and lawns became standard items in modern homes. Due to the very low water tariff, the community also developed wasteful water using habits such as keeping the taps running during bathing and other body cleaning activities, dish washing, fruits and vegetables cleaning and defreezing of frozen food. Water misuse during floor washing and garden watering became common place too. Unattended leaks inside consumers' premises also constituted a substantial proportion of municipal water consumption. The Water Conservation Department (WCD) was established in the early 90s to control municipal water consumption. Its activities included:

- Leak detection in consumers' premises
- Promotion of water conservation through the use of low cost water saving devices, low water consumption sanitary appliances and adopting low consumption water use habits.
- Public education and awareness campaigns to highlight the seriousness of the water crisis in Bahrain and the benefits of water saving.

The WCD estimated leakage in consumers' premises in 2004 at about 22000 m^3 per day and their work led to savings of up to 15% of that (Figure 8).

Investigations by WCD and the author of this paper (unpublished) into the effect of using simple low cost water saving devices such as tap aerators proved that they are economically feasible and can reduce consumption by up to 15% in residential units and 25% in non-residential units such as schools and mosques. Savings of up to 20% of domestic consumption were achieved using garden irrigation timers.

Demand Management

The old practice of Supply Management associated with a very low fixed water tariff led consumers to waste and misuse water. As a result, municipal demand was increasing beyond control. Two measures were introduced to deal with this part of the problem. These were:

- The introduction of metered water Rates
- Demand instead of supply management.

Table 2 summarizes the history of the tarrif for municipal water in Bahrain. The fixed monthly water tarrif that was first introduced in 1977 did not provide any incentive to the consumers to control their consumption. A new consumption related (increasing step tariff) was introduced in 1985 to control the demand. This new tariff exerted some pressure on the consumers to reduce their consumption because they are charged according to their consumption and the tariff increases with increase in consumption. It was estimated that application of the new tariff reduced consumption by 8 to 11% [14]. The tariff was reviewed several times before being eventually reduced to a nominal 0.025 BD per m^3 for the first 60 m^3 per month per residential unit, 0.080 BD for the next 20 m^3 and 0.2 BD per m^3 for more than 100 m^3. Accordingly, the tariff lost some of its effect.

Demand management is another effective consumption control measure. Under this system a limited amount of water is supplied to the distribution network every day and the consumers are left to adjust their consumption accordingly. Applying this system limited the consumption in the late 90s to abut 0.32 Mm^3/d (70 MIGPD), about 0.36 Mm^3/d (80 MIGPD) between 2000 and 2003 and 0.41 Mm^3/d (90 MIGPD) in 2004. Figure 9 represents the expected demands with and without this control.

Leak Detection in the Transmission and Distribution Networks

A substantial amount of municipal water is lost through leaks in the transmission and distribution networks. The Leak Detection Unit was established in the early 90s and upgraded later to a department to control these losses by detecting leaks, repairing and rehabilitating the networks. The Leak Detection Department (LDD) activities resulted in reducing network losses from about 29% (H" 31 Mm^3 per year) in 1996 to about 17% (H" 26 Mm^3 per year) in 2004 (Figure 7).

EXPECTED RESULTS

The authorities were expecting that applying the above described measures would result in substantial reductions in agricultural and municipal consumption leading to great reductions in groundwater abstraction which in turn would reduce the stress on groundwater resources and improve municipal water quality. Following are some of the expected results in more details:

In Agriculture

It was expected that application of the planned reforms in agriculture including introducing the tariff, replacing high water consumption crops with others of low water requirements, introduction of water efficient irrigation methods and technologies and installation of recycling systems on swimming pools would collectively reduce agricultural groundwater consumption by about 50 Mm^3 per year in 2002 [14]. Unfortunately, the tariff was never applied; therefore, farmers did not have the economic incentive to replace the traditional crops of high water requirements by others of high value and low water demand. Farmers also were not under any pressure to replace their traditional water wasting irrigation methods. Accordingly, the agricultural consumption rate began to increase to reach a maximum of about 4.5 m^3/m^2 by the late 90s. The observed decline in the total agricultural consumption from about 180 Mm^3 in 1999 to around 135 Mm^3 in 2003 was mainly due to the loss of about 12 km^2 of irrigated agricultural land during this period (Figure 4).

The government plans to produce 60 Mm^3 per year of TSE for use in agriculture also could not be achieved by 2002. For various reasons, there were serious delays in the construction of the distribution networks and farms connections. As a result, only around 20 Mm^3 per year of TSE is currently being utilized.

In the Municipal sector

It was expected that after commissioning of the 0.14 Mm^3/d (30 MIGPD) Phase 1 HPWS in 2000, groundwater abstraction for municipal use would be reduced by about 36 Mm^3 per year. Further reductions were expected as a result of rehabilitating Al-Door plant and expansion of HPWS (Phases 2 and 3) to have an ultimate production capacity of 0.41 Mm^3/d (90 MIGPD) by 2006 [14]. But reduction of only about 10 Mm^3 per year could be achieved in 2001. Phases 2 and 3 have not been implemented yet, Al-Door could not be rehabilitated and increase in demand reduced the initial savings in groundwater for domestic use to about 7 Mm^3 per year.

It was also expected that leakage in the transmission and distribution networks would be reduced to about 10% by 2000 [14]. Leakage was initially reduced from a record of about 29% (H" 31 Mm^3) in 1996 to less than 15% (H" 16 Mm^3) in 1999, but increase in pressure in the old networks following the commissioning of HPWS increased leakage to about 19% (H" 26 Mm^3) in 2002 before being slightly reduced to 17% (H" 26 Mm^3) in 2004 (Figure 7).

Improvements in Municipal Water quality

It was expected, following commissioning of Phase 1 HPWS and rehabilitation of the Al-Door plant by the year 2000, that the actual desalinated water production for municipal use would increase to about 0.32 Mm^3/d (70 MIGPD) and blending groundwater proportion would be reduced to about 0.045 Mm^3/d (10 MIGPD) only [14]. The TDS was expected by then to be reduced to about 600 mg/l (Figure 11). However, because as explained above, Al-Door plant could not be rehabilitated and work in Phases 2 & 3 of HPWS has not started yet, desalination production remained below 0.3 Mm^3/d (65 MIGPD) and groundwater contribution to the municipal supply remained at more than 30% (H" 29 MIGPD). The expected improvement to municipal water quality could not be achieved and the TDS level in municipal water still exceeds of the allowable WHO guideline limit.

CONCLUSIONS

Based on the above discussion, the following can be concluded:

- Although the solutions to the water crisis in Bahrain were well identified, implementation of these solutions was always incomplete and late allowing only limited positive results.
- The positive results achieved include utilization of about 20 Mm^3 per year of TSE, production of about 106 Mm^3 per year of desalinated water and saving of about 9 Mm^3 per year through water conservation activities and networks repair and rehabilitation.
- Some of the planned solutions such as the agricultural consumption tariff and Phases 2 and 3 of the HPWS were never applied. Consequently, the expected reductions in groundwater abstraction by about 146 Mm^3 per year by 2002 resulting from reforms in agricultural consumption, provision of alternative water resources and water conservation efforts could not be achieved.
- The current abstraction rate of about 195 Mm^3 is well above the target of 107 Mm^3 per year by 2002 (Figure 10). As a result, groundwater depletion, salt water intrusion and groundwater quality deterioration continues unabated. The current average TDS in municipal water of about 1400 mg/l is well above the target of 600 mg/l and the WHO guideline of 1000 mg/l.

RECOMMENDATIONS

In light of the above, the following recommendations can be made to allow sustainable use of groundwater in Bahrain:

In Agriculture

- Update and strengthen groundwater use legislations and enforce rules and regulations to optimize agricultural consumption.
- Enforce the use of TSE wherever it becomes available and stop the use of groundwater except for emergency situations.
- Extend TSE supply to all agricultural areas in Bahrain.
- Apply the proposed tariff on agricultural consumption.
- Promote the use of water conserving irrigation methods and technologies.

In the Municipal Sector

- Start construction of Phases 2 and 3 of HPWS without further delay.
- Intensify water conservation efforts and activities aimed at optimizing water use
- Involve the media, especially the TV, in public education and awareness campaigns about the water resources crisis in Bahrain and promotion of water conservation.
- Adopt policies to encourage water recycling and reuse.

- Intensify activities of leak detection, repair and rehabilitation of the water transmission and distribution networks.
- Review and adjust the water tariff, especially the second and third steps to reflect the true cost of water.

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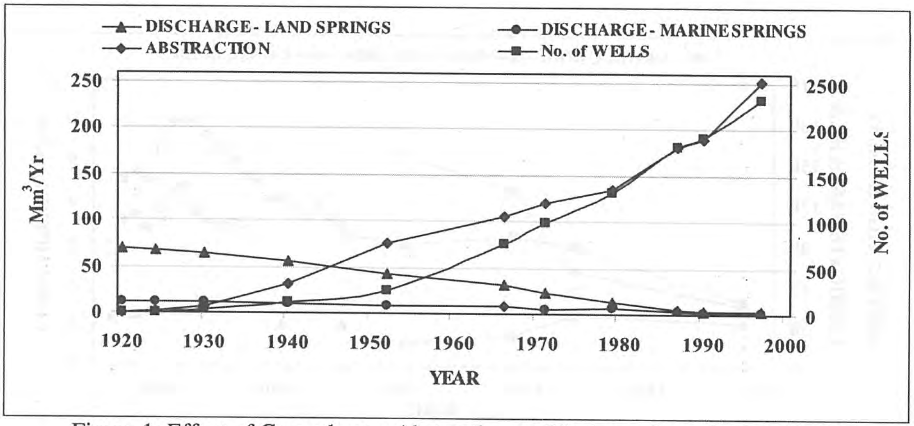

Figure 1: Effect of Groundwater Abstraction on Discharge from Springs [1, 5-9]

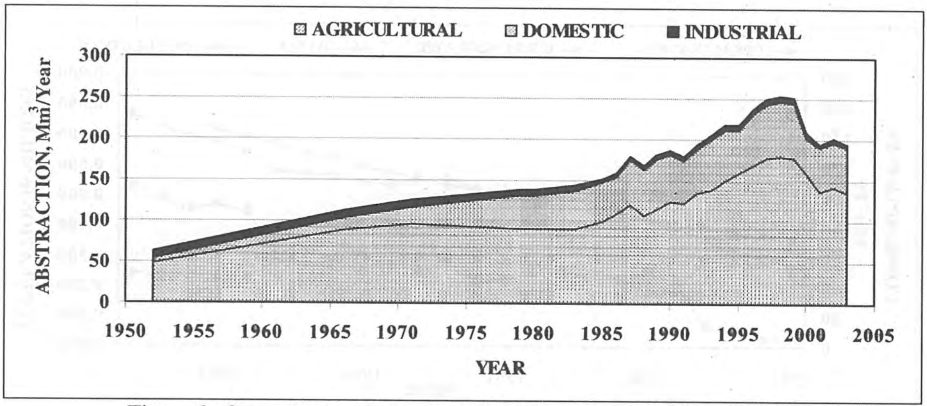

Figure 2: Groundwater Consumption by the Various Sectors [1, 5-9]

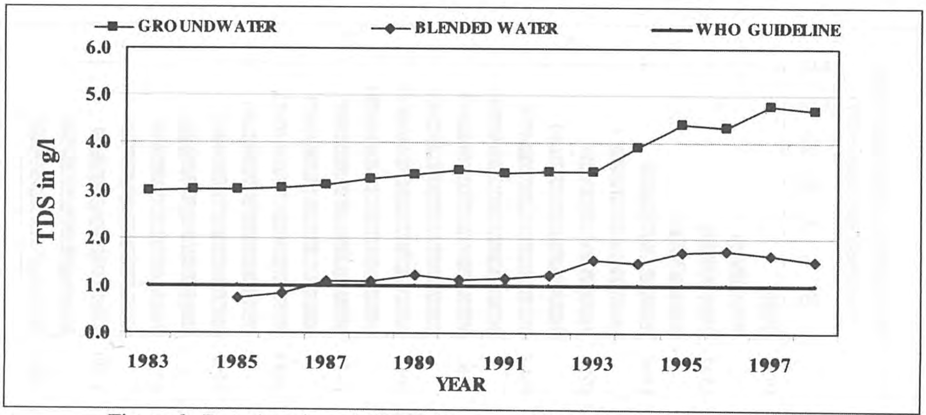

Figure 3: Deterioration of Groundwater and Blended Water Quality [10]

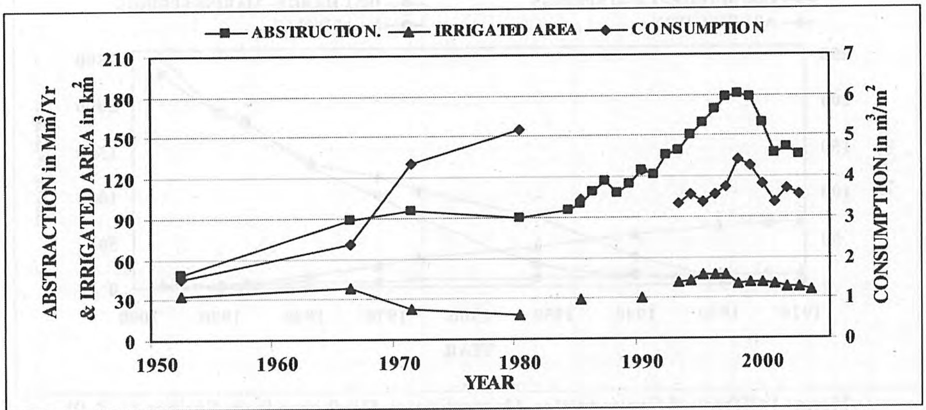

Figure 4: Development of Groundwater Consumption for Agriculture [9, 11 and 12]

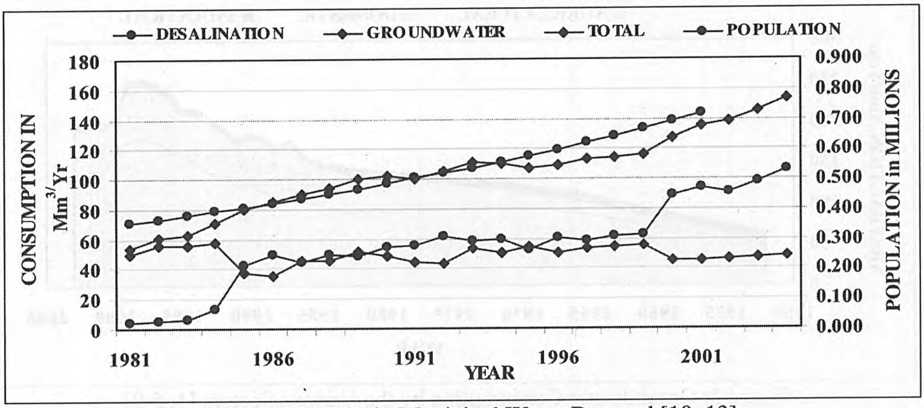

Figure 5: Growths in Municipal Water Demand [10, 13]

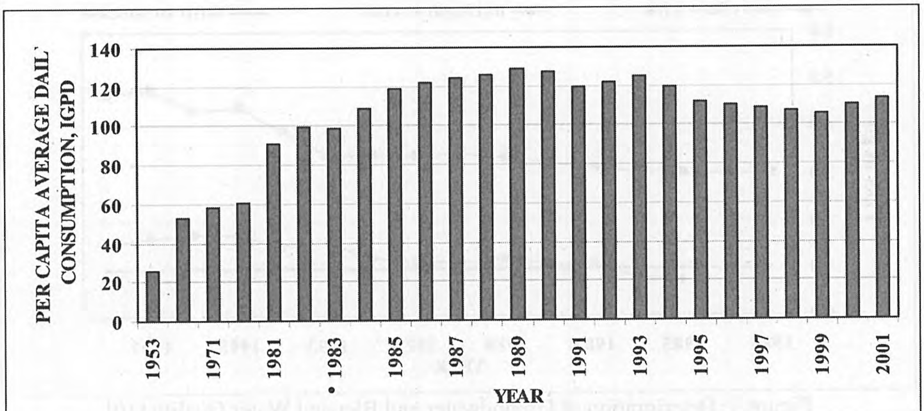

Figure 6: Variations in Per Capita Municipal Water Consumption [10]

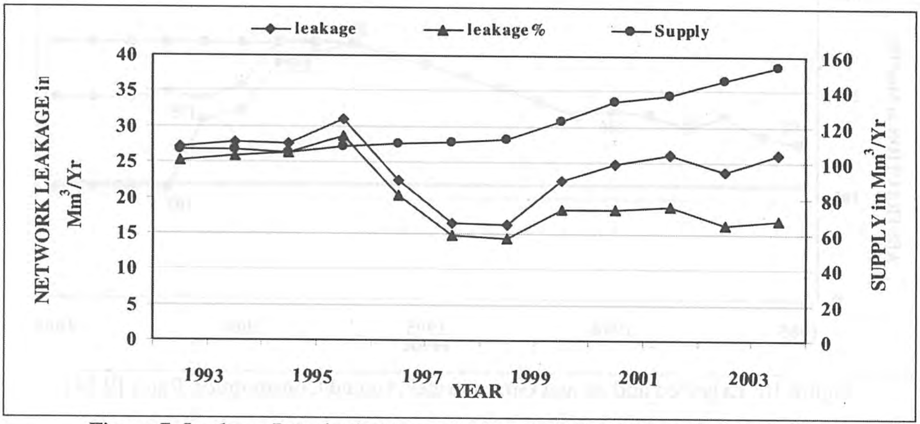

Figure 7: Leakage Rate in the Transmission and Distribution Networks [10]

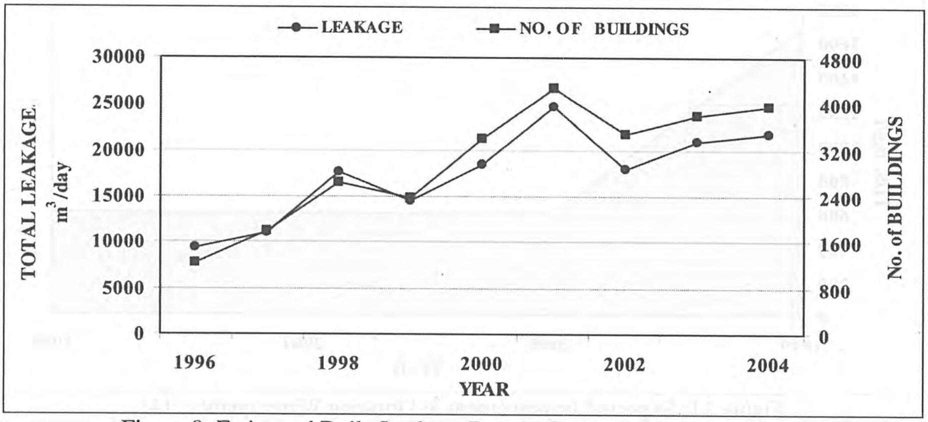

Figure 8: Estimated Daily Leakage Rate in Consumers' Premises [10]

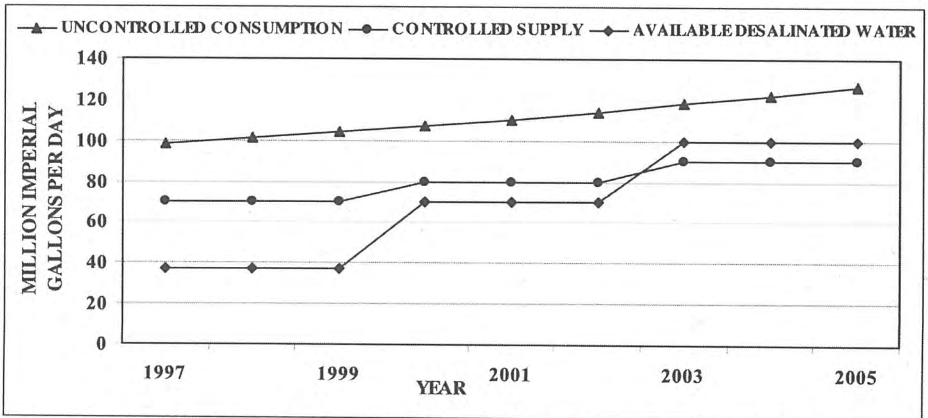

Figure 9: Expected Municipal Demands With and Without Control [14]

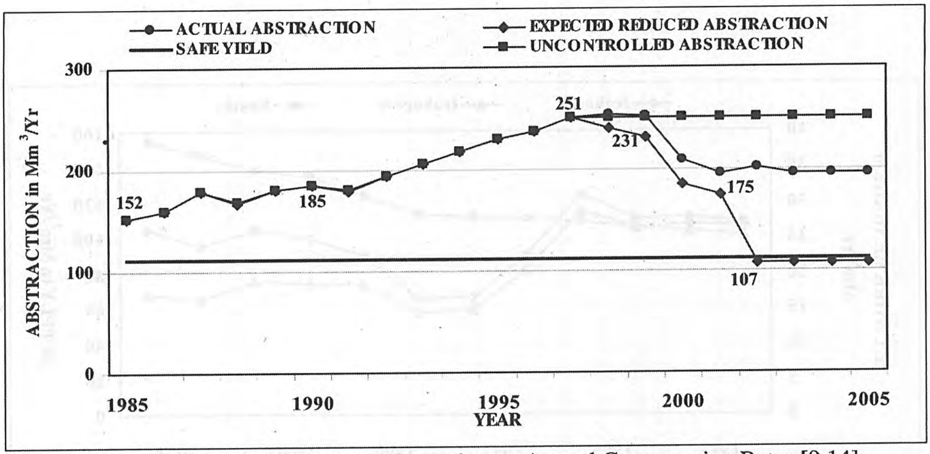

Figure 10: Expected and Actual Groundwater Annual Consumption Rates [9,14]

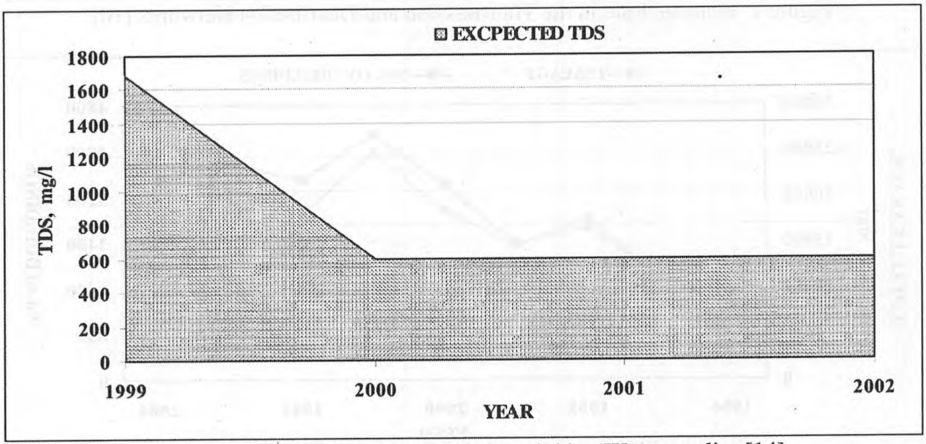

Figure 11: Expected Improvement in Drinking Water quality [14]

Table 1 Development of Desalination Production Capacity [10]

PLANT NAME	DATE OF COMMISSIONING	CAPACITY in MIGPD*
SITRA MULTISTAGE FLASH EVAPORATION	1A 1975	2.5
	18 1979	2.5
	2 1984	5
	3 1985	5
	4 1985	5
	5 1985	5
SUBTOTAL		**25**
RAS ABUJARJOOR RO	1984	12.5
ADOOR RO	1990	10
HIDD MULTISTAGE FLASH EVAPORATION	13 1999	7.5
	14 1999	7.5
	15 1999	7.5
	16 1999	7.5
SUBTOTAL		**30**
TOTAL		**77.5**

* 1 Imperial Gallon = 4.546 litres
220 Imperial Gallons

Table 2: Development of Municipal Water Rates

RATES FOR GROUNWATER			
DATE	**USE**	**CONSUMPTION**	**TARIFF**
1977-1990	DOMESTIC/NONDOMESTIC	FIXED MONTHLY RATE	0.800 BD
1990-1992	DOMESTIC/NONDOMESTIC	1-50 m^3 PER MONTH 51- 100 m^3 >100 m^3	1.5 BD (FIXED) 0.035 BD per m^3 0.085 BD per m^3
1992-2004	DOMESTIC/NONDOMESTIC	1-60 m^3 PER MONTH 61- 100 m^3 >100 m^3	0.020 BD per m^3 0.025 BD per m^3 0.085 BD per m^3
May 2004	DOMESTIC	1 - 60 m^3 PER MONTH 61 - 100 m^3 > 100 m^3	0.025 BD per m^3 0.080 BD per m^3 0.200 BD per m^3
	NONDOMESTIC	1-450 m^3 PER MONTH > 450 m^3	0.300 BD per m^3 0.400 BD per m^3
RATES FOR BLENDED WATER			
April 1985	DOMESTIC	1 - 45 m^3 PER MONTH 46 - 65 m^3 > 65 m^3	0.045 BD per m^3 0.11 BD per m^3 0.450 BD per m^3
	NONDOMESTIC	1-450 m^3 PER MONTH > 450 m^3	0.450 BD per m^3 0.770 BD per m^3
September 1985	DOMESTIC	1 - 50 m^3 PER MONTH 51 - 100 m^3 101 - 150 m^3 > 150 m^3	0.045 BD per m^3 0.11 BD per m^3 0.200 BD per m^3 0.450 BD per m^3
	NONDOMESTIC	1-450 m^3 PER MONTH > 450 m^3	0.450 BD per m^3 0.770 BD per m^3
November 1986	DOMESTIC	1 - 50 m^3 PER MONTH 51 - 100 m^3 > 100 m^3	0.045 BD per m^3 0.110 BD per m^3 0.200 BD per m^3
	NONDOMESTIC	1-450 m^3 PER MONTH > 450 m^3	0.300 BD per m^3 0.400 BD per m^3
May 1992	DOMESTIC	1 - 60 m^3 PER MONTH 61 - 100 m^3 > 100 m^3	0.025 BD per m^3 0.080 BD per m^3 0.200 BD per m^3
	NONDOMESTIC	1-450 m^3 PER MONTH > 450 m^3	0.300 BD per m^3 0.400 BD per m^3

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Water in the GCC - Towards an Integrated Management

19 - 23 November 2005, State of Kuwait

DEVELOPMENT & MANAGEMENT OF NATURAL WATER RESOURCES

a) GROUND WATER RESOURCES

State of water resources in the ESCWA region

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STATE OF WATER RESOURCES IN THE ESCWA REGION

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ABSTRACT

The state of water resources in the ESCWA Region is analyzed and assessed on the basis of data and indicators selected from available information and within the context of indicators adopted by the World Water Assessment Programme (WWAP). A total of 29 indicators have been identified and a DPSIR (Driving forces for water use, Pressures, State, Impact, and Response) framework is used to assess the state of water resources in the Region. The assessment includes *data adequacy; water resources availability; land and water resources use; dependency and accessibility;* and *sustainability of use*. The result can be summarized as following:

Data adequacy: Information on water resources in the ESCWA region is limited in scope. Using the DPSIR approach, the current indicators can be broken down into 5D, 8P, 5S, and 11P. The fact that no indicators are available on the impact (I) of the present use on the society and/or ecosystem is alarming in the sense that the benefits of water use and its negative effects on the environment still remain obscure.

Water resources availability: Most of the ESCWA countries are currently under "water poverty" conditions. The freshwater available to all countries, with the exception of Iraq and possibly Syria, is below the water resource base of 1000 m^3/p/y. Hence they, are presently suffering from a "water poverty" even when the supplementary volumes of water produced from non-conventional sources are considered. The situation is particularly serious in Jordan and Yemen where "water poverty" is compounded by low national capital income.

Land and water resources use: Most of the available freshwater in the Region is being consumed in agricultural development that hardly contributes to national economies. Agricultural water requirement has increased from 123.3 bcm in 1990 to 146 bcm in 2005. The economic return from agricultural development is generally very poor in most countries (<10%) and agricultural economic efficiency has been less than 1.0 since 1995 in all countries except Iraq and Lebanon.

Dependency and accessibility: A very significant portion of the freshwater from natural sources consumed in Bahrain (96.5%), Egypt (96.9%), Iraq (53.3%), Kuwait (100%) and Syria (73.4%) and, to lesser extent, Jordan (22.2%), Palestine (1.2%) and Qatar (3.8%), comes from outside the political boundaries of these countries. The dependency on internationally shared water is particularly important for Egypt, Iraq and Syria because of the substantial volumes of water from external sources. With respect to accessibility, the total domestic water demand in the ESCWA region has increased from 10.5 bcm (1990) to 16.7 bcm (2005) and is expected to reach 27.6 bcm in 2025. This means about

11 bcm or only 7% of the present consumption in the agricultural sector would be needed to satisfy the growing domestic water needs over the coming 20 years.

Sustainability of use: Higher water use intensities are hindering sustainability of water resources in many ESCWA countries. Water use intensity, or the ratio of per capita fresh water use to per capita fresh water resources, characterizes most of the ESCWA countries. When these intensities are translated to water deficit, the Member States can be grouped into two categories: those with water deficit (Egypt, Kuwait, Oman, Palestine, Qatar, Saudi Arabia, United Arab Emirates and Yemen) and those without (Bahrain, Iraq, Lebanon, Jordan and Syria). Of the countries with water deficit, the stress related to water use, in terms of the number of persons per unit flow, is particulrly serious in Yemen and Palestine.

1. INTRODUCTION

Water is a very scarce commodity in the ESCWA region, one of the most arid areas in the world. The severe water-related problems in the Region have been compounded in recent years by a sharp increase in water demand due mainly to the fast growing population in most of the ESCWA countries. Throughout the last quarter of the previous century, the implications of this increase in water demand have been overshadowed by the Region's preoccupation with industrial and socio-economic development issues, resulting mostly from the economic boom of oil in the Gulf area that slowly but undoubtedly affected neighboring ESCWA countries. In the absence of effective control measures and/or regulating mechanisms, over-exploitation of the limited water resources available in the region has continued in a rapid and irrational manner. With the availability of vast areas of uncultivated arable land in the Region, especially in non-GCC countries, it was natural that irrigation takes the biggest share of water and becomes the prime driving force for the increasing demand and, hence, un-sustainability of the resources. Like many other parts of the world, however, the ESCWA region is witnessing a dramatic shift in priorities in recent years towards a more sustainable use of the available resources. Irrigation, which was seen as an essential step towards the achievement of self-sufficiency in food production throughout the 1970s and 80s has been regarded in the late 1990s as a low-value use for water in comparison with municipal and industrial uses. Many countries in the Region are also beginning to include environmental protection in their national plans in order to give the ecosystem its fair share of the available water for maintaining itself and sustaining the fauna and flora while allowing also effective recharge of the aquifer systems.

The triggering effect of the water problem in the ESCWA region is the 'socio-economic dilemma' of developing countries situated in a typical arid and semi-arid environment where water and/or financial resources are limited. On one hand, these countries try to provide the necessary water and food required for the well being/decent living of their population and self-autonomy of the state. On the other, they strive to attain the industrial and economic development levels necessary for maintaining modern-day affluent way of living for the largest portion of the population. Hence the gap between the three main water-use sectors (domestic, industrial and agricultural) becomes bigger over the years. It is estimated that the water requirements of these sectors, in terms of million cubic meters (mcm), will increase dramatically in the ESCWA region over the next 20 years as shown below (ESCWA, 2003):

Sector water use	**2000**	**2025**
Domestic water use, mcm	13,866	30,244
Agricultural water use, mcm	150,697	192 266
Industrial water use, mcm	16 498	25 243
Total	**181061**	**247753**

Based on the above projected figures, the total demand for water in the ESCWA region for the year 2000 (18 1061 mcm) is expected to increase by about 50% to 247 753 mcm by the year 2025. If we recall that the total demand for 2000 was roughly equal to the total volume of fresh water available from all sources, estimated for that year at about 179 494 mcm from both conventional (169 247 mcm) and non-conventional (10 247 mcm) sources, it can be envisaged how aggravated the water problems would be in the year 2025. With this realization, the ESCWA countries are beginning to take measures for the application of integrated water resources management (IWRM) concepts towards a more sustainable use of the limited water resources in the Region. For this and in order to monitor the implementation of such concepts, a set of indicators are needed that would basically address the three principal targets for IWRM: social welfare and equity; economic efficiency; and environmental sustainability. Such indicators should, moreover, represent the three sub-systems of an integrated water resources system: natural sub-system that supplies the water; socio-economic sub-system or boundary conditions for any sustainable development; and institutional-legal sub-system that provides the framework for enhancing IWRM application.

Water-related data in ESCWA countries is usually fragmented in several governmental organizations and it is only recently that a number of the Member States started establishing specific ministries or centralized agencies responsible for the management of water resources. These authorities are now focusing on obtaining all available information such that a comprehensive database can be established. Notwithstanding that the prime responsibility of these authorities is to monitor the status of the available water resources, and considering the paucity and extreme difficulty in obtaining water-related socio-economic and institutional-legal information at this stage, the prime objective of this paper is to provide a comprehensive understanding of the state of water resources in the ESCWA region. Analysis of all available data/information is undertaken to determine freshwater availability in each of the 13 Member States, the current sectoral use, especially in the agricultural sector that consumes a good portion of the water, the dependency and accessibility levels to the available resources, and their sustainability.

2. DEVELOPMENT OF BASIC WATER INDICATORS IN THE ESCWA REGION

Indicators on Integrated Water Resources Management (IWRM) are comprised of measurements and derived values that track the changes of water resources conditions and their management efforts and success/failure over time. They help measure the state of water resources in general, the pressures exerted on them, and the resulting impacts on ecological and human health. More importantly, such indicators show progress of measures and policies aiming at the protection and sustainable development of water resources. Indicators used for enhancing the application of IWRM concepts at national and/or regional levels must provide information on:

- availability of water resources
- demand on these resources
- accessibility of the population to the resources, and
- sustainability of the resources for future generations

As suggested by the United Nations World Water Development Report (WWDR-1) that was published in 2003 water indicators must at the same time provide:

1. Decision-makers with a means to understand the importance of water issues so as to involve them in promoting effective water governance,

2. Water specialists with a way to step 'outside the water box', so they learn to take into account broader, social, political and economic issues into the water equation, which would then require,

3. transparent and mutually communicable strategies for decision-makers and water specialists, in such a way that both have a clear understanding of the state of progress in terms of a global desire to achieve water-related goals and targets through effective implementation of policies and related actions.

2.1 The DPSIR Framework for Indicators Development

Two main issues stand out as the primary drivers for indicator development:

1. The need to present complex phenomena in meaningful, understandable, comparable and objective numbers to decision-makers and the public, and
2. The need to establish objective benchmarks and analyze changes over time and space.

A suitable framework is needed for organizing the process of selecting and developing indicators, such as that indicated in Box 1. The choice of a framework and a core set of indicators must meet the needs and priorities of users, in this case national experts, civil society groups and decision makers responsible for the development and use of indicators to monitor progress towards sustainable management of water resources. It should be stressed that any country wishing to use indicators, in any systematic way, must develop its own program drawing on the resources currently available.

Box 1:
Why a framework is needed?

- Link data to decision making
- Structure the collection, analysis, and presentation of information
- Identify data gaps and duplications
- Assist in developing new data to fill data gaps

The major indicator development models appear to have been shaped by four approaches: Bottom-up approach, Top-down approach, Systems approach, and Cause-effect approach commonly known as the Pressure-State-Response (PSR), or the Driving force-Pressure-State-Impact-Response (DPSIR). The latter has been selected as the appropriate approach for the World Water Development Series which has also been adopted by ESCWA.

The advantage of the PSR approach, introduced by the Organization for Economic Co-operation and Development (OECD) in 1994, is that it enabled trade-offs and the linking of environmental, economic and social indicators. Following this approach, and with the need to expand the framework to deal more specifically with human activities that impact on sustainable development either positively or negatively, the DPSIR has evolved as the most widely used indicator framework for the analysis of water resources issues by the UN and other international organizations.

In accordance with the DPSIR framework (Figure 1), social and economic changes related to development (population growth, agricultural policies, food demand, and new technology innovations) coupled with the aridity prevailing in most of the ESCWA region, constitute driving forces that cause different kinds of pressures (socio-economic, hydropolitical and environmental). As a consequence, the state of water resources, in terms of both quantity and quality, may deteriorate leading to impacts on the society as well as the ecosystem. These impacts would elicit responses in the form of societal measures to relieve some of the pressures from the system, in terms of effective water policies, or by spontaneous responses from the natural system to adjust itself to the increasing pressures.

2.2 Application of the DPSIR Framework to Develop Water Related Indicators in the ESCWA Region

Water data and other related information on the status of water resources in ESCWA countries comes from various government organizations that deal with water issues but may or may not be mandated with the management of the resources. Hence the information available may be quite diversified, fragmented, incompatible, of limited scope, and often not updated or closely scrutinized for effective management plans. For the purpose of this study, all available information was compiled and scrutinized. The following steps were then taken to put this information in a DPSIR framework:

1. Itemizing the information into 2 main groups: data and indicators, as the nature of information presently available in ESCWA countries does not allow aggregation to the level of indices at this stage.
2. Preparing a complete list of the most up-to-date water-related information, complied on a country-by-country basis.
3. Breaking down the main list into 5 categories: general socio-economic data; water resources availability; land and water resources use; sustainability of use and accessibility; and basic indicators.

Categorizing each indicator in accordance with the DPSIR framework.

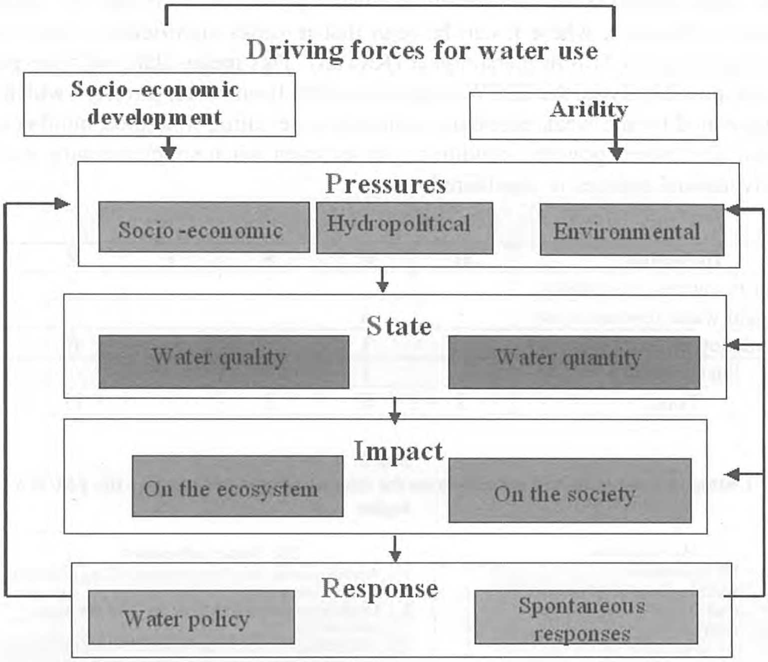


Figure 1: Proposed DPSIR framework for ESCWA

A total of 57 data points have been identified for each country: 28 basic data, 29 basic indicators (Box 2). Of the 29 indicators, there are 11R, 8P, 5D and 5S as indicated below. The choice between the D and P indicators is not a clear-cut one but that does not really change the picture significantly. No indicators whatsoever are available on the impact (I) of water use. Hence it is evident that there is a need to develop new indicators on the impact of the current use of these resources on both the society and the ecosystem. It is also clear that more indicators on the state of the water resources would be very useful, especially with respect to their quality.

3. WATER RESOURCES AVAILABILITY

The volume of surface water available in the ESCWA region far exceeds groundwater. The bulk of surface water, however, is in major rivers (Nile, Tigris and Euphrates) that supply only Egypt, Iraq and Syria. Groundwater, despite being less than surface water in terms of volume, remains a more common source of water to most of the countries in the Region. Availability of water within the ESCWA region varies from country to country not only in terms of volume but also in terms of the source of this water. Basic data and indicators used for assessing the supply side of water resources in the region, based on the type and nature of the various sources of fresh water available in different countries, are discussed below.

3.1 Per Capita Annual Share from Renewable Water Resources

The per capita annual share from renewable water resources in the ESCWA countries is displayed in Figure 2, where it can be seen that it varies significantly from 3066 m^3/person/year (Iraq) to 71.8 m^3/person/year (Kuwait). This means that, with the exception of Iraq and possibly Syria, the ESCWA countries suffer from 'water poverty', which usually gets aggravated by the weak economic conditions prevailing in a good number of these countries. The 'water poverty' conditions persist even when supplementary water from non-conventional sources is considered.

Indicator	**D**	**P**	**S**	**I**	**R**	**Total**
Water resources availability			2		5	7
Land and water resources use	5	6				11
Dependency and accessibility		1	1		6	8
Sustainability		1	2			3
Total	**5**	**8**	**5**		**11**	**29**

Box 2:
Listing of basic data and indicators on the status of water resources in the ESCWA region

2A: Basic data

1. Total population
2. Annual population growth rate
3. Annual population growth rate
4. Total GDP *(constant prices)*
5. Per capita GDP
6. Total surface water
7. Mean annual groundwater recharge
8. Total renewable water resources
9. Mean annual production of desalinated water
10. Mean annual production of treated wastewater for reuse
11. Mean annual production of agricultural drainage for reuse
12. Total water resources from non-conventional sources
13. Mean annual water use for domestic purposes
14. Mean annual water use for agricultural purposes
15. Mean annual water use for industrial purposes
16. Total water use
17. Total land
18. Total agricultural land
19. Total cultivated land
20. Total irrigated land
21. Agricultural GDP *(constant prices)*
22. Total groundwater abstraction
23. Urban population with access to improved drinking water
24. Rural population with access to improved drinking water
25. Total population with access to improved drinking water
26. Urban population with access to improved sanitation
27. Rural population with access to improved sanitation
28. Total population with access to improved sanitation

2B: Basic indicators

1. Available surface water as a percentage of total renewable water resources (S)
2. Groundwater as a percentage of total renewable water resources (S)
3. Per capita annual share from renewable water resources (R)
4. Per capita annual share from non-renewable water resources (R)
5. Desalinated water produced as a percentage of total renewable water resources (R)
6. Treated wastewater and agricultural drainage produced as a percentage of total renewable water resources (R)
7. Non-conventional water resources produced as a percentage of renewable water resources (R)
8. Domestic water use as a percentage of total water use (D)
9. Per capita domestic water use (P)
10. Agricultural water use as a percentage of total water use (D)
11. Per capita agricultural water use (P)
12. Industrial water use as a percentage of total water use (D)
13. Per capita industrial water use (P)
14. Agricultural land as a ratio of total land (P)
15. Cultivated land as a ratio of total land (D)
16. Irrigated land as percentage of agricultural land (P)
17. Agricultural GDP as a percentage of total GDP (D)
18. Agricultural economic efficiency (P)
19. Groundwater abstracted as a percentage of total water resources used (S)
20. Per capita use of fresh water resources (P)
21. Urban population with access to improved drinking water as a ratio of total urban population (R)
22. Rural population with access to improved drinking water as a ratio of rural population (R)
23. Total population with access to improved drinking water as a ratio of total population (R)
24. Urban population with access to improved sanitation as a ratio of total urban population (R)
25. Rural population with access to improved sanitation as a ratio of rural population (R)
26. Total population with access to improved sanitation as a ratio of total population (R)
27. Water use intensity (P)
28. Water deficit (S)
29. Water stress (S)

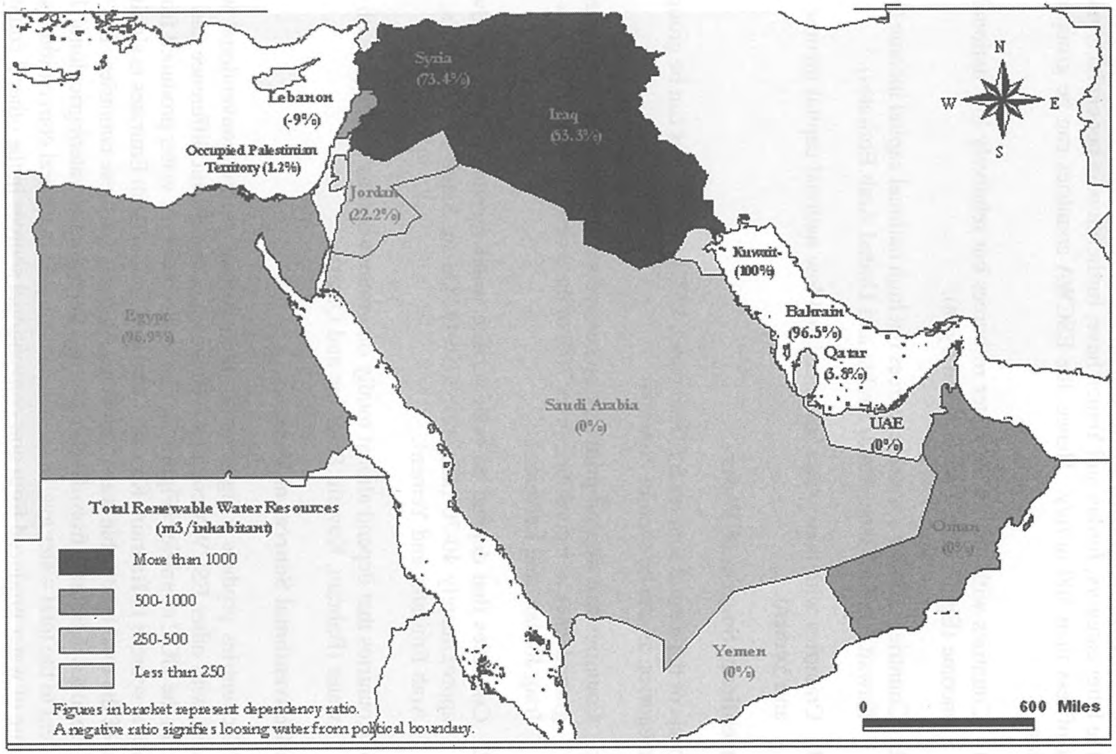


Figure 2: Water resource in the ESCWA region
(Total Renewable Water Resources and Development Ratios)

With the exception of Iraq, the total per capita water available across the Region is below the level of what is estimated for a typical semi-arid environment (ca 1350 $m^3/p/y$; SIWI, 2002).

With respect to the national capital income, ESCWA countries can be broadly divided into two main categories: the 6 GCC 'rich' countries that have a GDP per capita income in excess of 5,000 \$/person and the remaining 'poor' countries with less than that (Figure 3). Within the latter category, Jordan and Yemen have, furthermore, a per capita annual share of water of less than 500 $m^3/p/y$. Hence, the ESCWA countries can be grouped into 3 categories:

Group 1: Countries with reasonable water resources but relatively low national capital income (Egypt, Iraq, Lebanon and Syria).

Group 2: Countries with poor water resources but high national capital income (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia and United Arab Emirates).

Group 3: Countries with poor water resources and low national capital income (Jordan and Yemen).

3.2 Conventional Sources of Water

On the basis of the natural sources for fresh water, ESCWA countries can be grouped also into 3 categories, as can be seen in Figure 4:

Group1: Countries that depend primarily on surface water resources as compared with groundwater, as it constitutes over 70% of the renewable water resources (Egypt, Iraq, Jordan, and Lebanon).

Group 2: Countries that depend on both surface water resources and groundwater at approximately 40-70 ratio, respectively (Oman, Saudi Arabia, Syria, United Arab Emirates and Yemen).

Group 3: Countries that depend almost totally on groundwater as compared with surface water (Bahrain, Kuwait, Palestine and Qatar).

3.3 Non-Conventional Sources of Water

The GCC countries produce a significantly high volume of non-conventional water in comparison with other ESCWA countries. However, a significant difference can also be seen within the GCC countries (Figure 5). The total volume of water produced from non-conventional sources in Bahrain, Kuwait, Qatar and United Arab Emirates is significantly in excess of the total renewable water resources available for these countries. The volume of water produced in Bahrain from desalination and treated wastewater/agricultural drainage is equivalent to the total water available to this country from natural conventional sources. The volume of water produced from non-conventional sources in the other 3 countries, as compared with conventional sources, is almost 2-3 times. It is clear from Figure 4 that these 4 GCC countries have become dependent mainly on desalination for most of their daily uses. The other 2 GCC countries (Oman and Saudi Arabia), however, are still dependent largely on renewable water resource despite the fact that Saudi Arabia produces close to 80% of all the water produced from non-conventional sources in the remaining 5 GCC countries.

The situation in the non-GCC countries is very different in the sense that (1) there is significantly less water produced from non-conventional sources as compared with conventional sources (<20%), and (2) there is more treated and agricultural drainage recycled for use, as compared with desalination (Figure 4).

Figure 3: Per Capita Annual Share from Renewable Water Resources vs. GDP per Capita

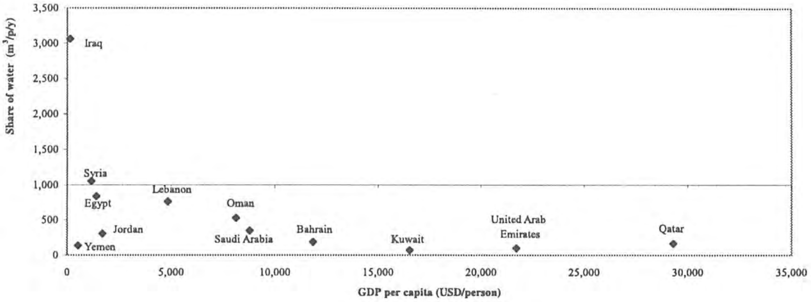


Figure 4: Available surface and ground water as percentage of total renewable water resources

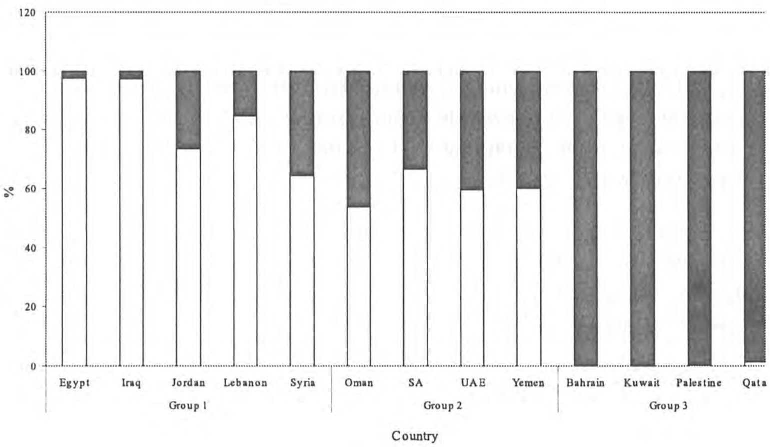
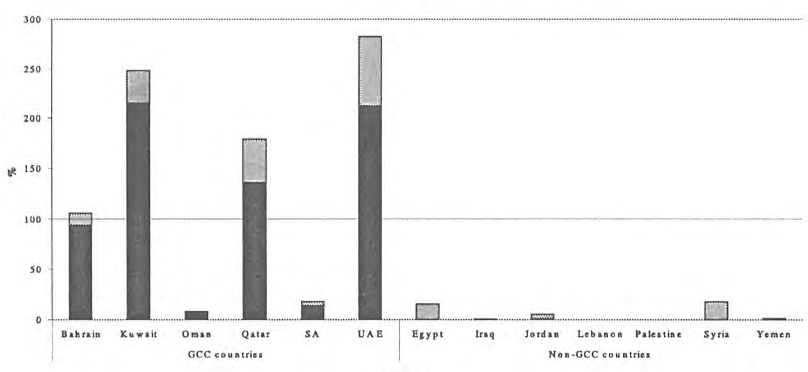


Figure 5: Desalinated water, and treated and agricultural drainage as percentage of total renewable water resources



4. LAND AND WATER RESOURCES USE

4.1 Water Resources Use

The general picture for water use across ESCWA's member States is shown in Figure 5. The per capita annual consumption in the 3 main sectors (domestic, agricultural and industrial) is discussed below.

4.1.1. Domestic water use

The ESCWA region has been characterized with a relatively sharp increase in the population throughout the 1980s and 1990s. Recently, however, a significant decrease in the growth rate is observed in most countries. Nevertheless, the total population in the Region in the year 2025 is expected to be close to double what it was in 1995 (Figure 7). Over 50% of the current population in the Region is in Egypt and Iraq (Figure 8). These 2 countries presently account for 64% of the Region's total domestic water use (38% and 26%, respectively), estimated at 16.7 billion cubic meters (bcm), despite the fact that the per capita domestic water use in these 2 countries remains at a relatively low rate compared with the GCC countries. This trend is expected to persist until the year 2025 at least, when the total domestic water use is expected to reach 27.6 bcm. It is also interesting to observe that:

- Oman and Saudi Arabia, which as mentioned earlier are the only two GCC countries that depend largely on renewable water resources, have relatively lower per capita consumption than the remaining GCC countries and that depend heavily on non-conventional water resources;

- domestic water use, as a percentage of total water use, is less than 10% in Member States with relatively large populations (Egypt, Iraq, Saudi Arabia, Syria, and Yemen) as compared with the less populous States where current domestic use represents about 25-45% of the total water use;

4.1.2. Agricultural water use

The per capita agricultural water use ranges widely from 7.6 m^3/p/y (Kuwait) to about 2074 m^3/p/y (Iraq) as shown in Figure 9. This means that with the exception of Iraq, all Member States are presently using significantly less water than required for growing enough food in an arid and semiarid environment such as that prevailing in the Region (ca. 1000 m^3/p/y; SIWI 2000). In terms of percentage, agricultural water use represents 3.8% in Kuwait and 93% in Yemen, with the remaining countries falling in between. Total agricultural water use in the Region is presently estimated at about 146 bcm, over 70% of it being consumed in Egypt and Iraq alone.

Agricultural water use represents about half the total use of water in Bahrain, Jordan, Lebanon, Oman, Palestine, and United Arab Emirates where freshwater from natural sources and/or cultivable land may be limited. Countries may possess relatively abundant surface water from perennial rivers (Egypt, Iraq, and Syria) or seasonal flash floods (Oman, Saudi Arabia, and Yemen) and/or cultivable land use over 75% of their water in the agricultural sector. The economic return from this sector is generally very poor in most countries (<10%) except in Syria (24.4%), Egypt (15.5%) and Yemen (14%) as shown in Figure 9. Agricultural economic efficiency (agricultural GDP divided by agricultural work labor force, Arab Monetary Fund, 2005) has been less than 1.0 since 1995 in all countries except Iraq and Lebanon as shown in Figure 10. This means that productivity of the work force in the agricultural sector is very low, particularly in Egypt, Syria and Yemen where agricultural GDP is relatively high. A possible explanation for this could be the availability of cheap labor from local rural populations in these countries.

Figure 6: Water use by sector in ESCWA member countries

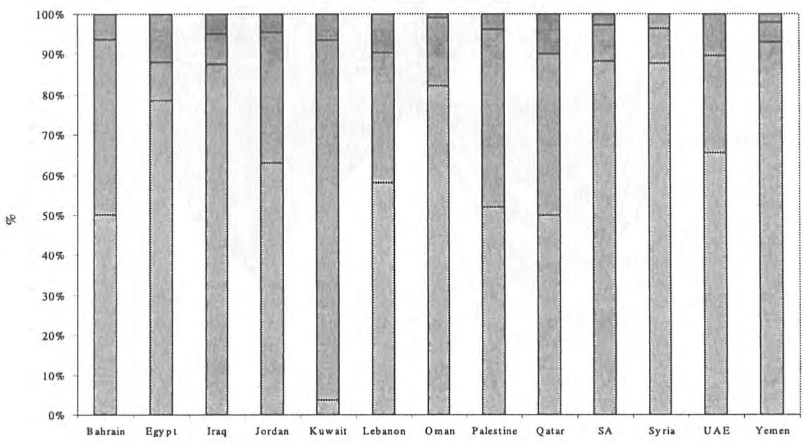


Figure 7: Population in the ESCWA Region (1995-2025)

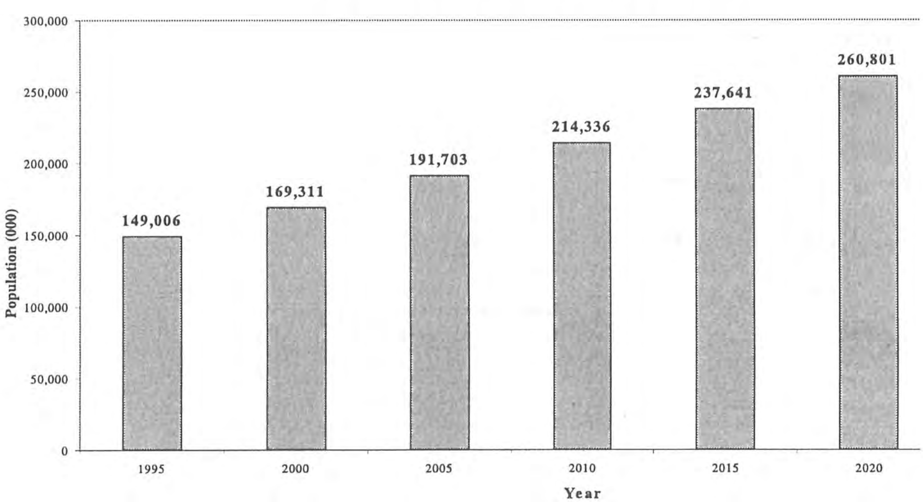


Figure 8: Population in ESCWA Member Countries (2005)

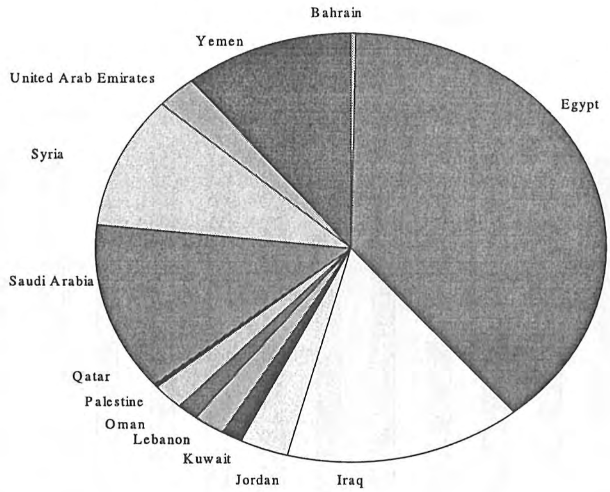


Figure 9: Agricultural GDP as a percentage of total GDP

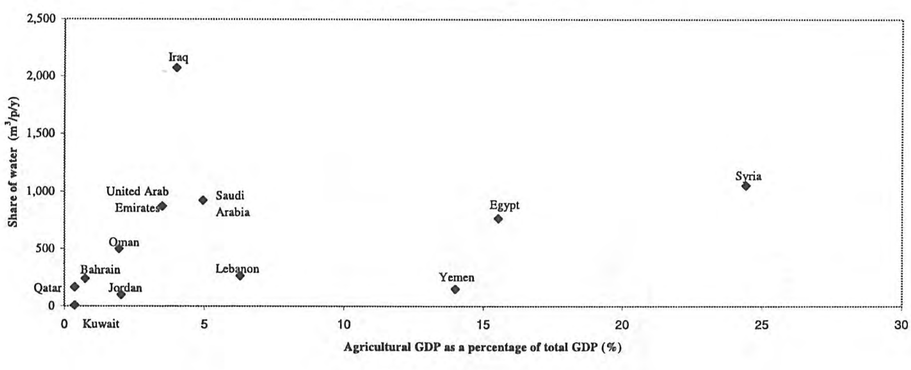
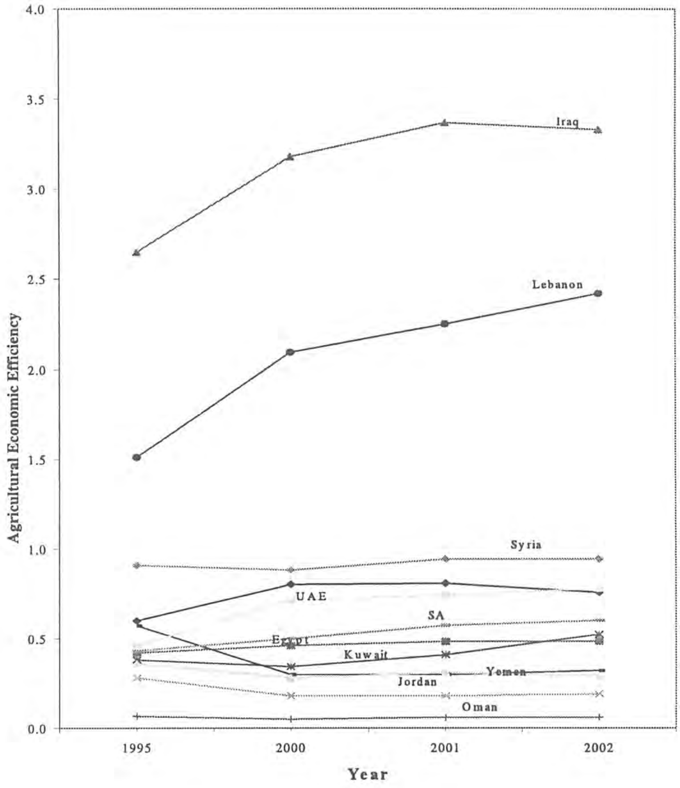


Figure 10: Agricultural Economic Efficiency in ESCWA Countries



4.1.3. Industrial water use

A total of 12.6 bcm is presently used by the industrial sectors across the ESCWA countries, with over 85% of this water being consumed in Egypt and Iraq (ESCWA, 2005). The proportion of water used in the industrial sector, in comparison with the domestic and agricultural sectors, is the lowest in all ESCWA countries except Egypt where 11.8% of total water use is consumed by industry as compared with 9.6% for domestic use. It is interesting to note that while the per capita use in Egypt and Iraq is comparable, it represents in Iraq only half of what it represents in Egypt in terms of percentage of total water use.

4.2 Land Use

The total area of the ESCWA region is estimated at 4.73 million km^2, according to the latest information available (FAO, 2003). Egypt and Saudi Arabia account for two-thirds, or 66.6% of the total land (21.1% and 45.5%, respectively). Saudi Arabia is also among four countries in the region that have agricultural land of over 25% of the total land area, the other three being Lebanon, Palestine, and Syria (ESCWA, 2005). Agricultural land in the remaining nine countries represents only less than 10% of the total area. At the present, six countries are cultivating practically all agricultural land within their territories (Bahrain, Egypt, Jordan, Lebanon, Syria, and United Arab Emirates). Iraq, Kuwait, Oman, Palestine, Qatar, Saudi Arabia, and Yemen have a major portion of agricultural land still not cultivated. It is also observed that 11 of the Member States are presently irrigating only about one-third or less of the cultivated land. Egypt and Bahrain are irrigating 100% and 66.7% of the agricultural lands, respectively (ESCWA, 2005).

5. DEPENDENCY AND ACCESSIBILITY

5.1 Dependency Ratio

Iraq has a per capita use of fresh water of about 2350 m^3/p/y, which is significantly higher than in all other Member States (Table 1). Egypt, Saudi Arabia, Syria and United Arab Emirates have a per capita use of circa 1000 m^3/p/y, slightly below the 1350 m^3/p/y level estimated for the needs of a typical semi-arid environment. The per capita use in the remaining countries (Bahrain, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar and Yemen) is far below this limit. All countries satisfy their needs for fresh water mainly from groundwater except Egypt, Iraq and Lebanon, which depend primarily on surface water.

A significant portion of the freshwater regardless of whether surface water or groundwater consumed by Bahrain, Egypt, Iraq, Kuwait and Syria and, to lesser extent, Jordan, Palestine and Qatar, comes from outside the political boundaries of these countries (Table 2). In the case of Palestine, only Gaza Strip is dependent on external water, at a ratio of 17.9% of the renewable water resources available in this coastal strip. If the calculation is made on the basis of the total renewable water resources in both Gaza and the West Bank, then the ratio drops to 1.2%. The dependency on internationally shared water is particularly important for Egypt, Iraq and Syria because of the substantial volumes of water from external sources. Lebanon is the only country that has a 'negative dependency' as it looses some of its fresh water to neighboring countries. Table 2 suggests that Oman, Saudi Arabia, United Arab Emirates and Yemen have zero dependency on external water resources. This is not entirely true, however, since it is known that these countries share some groundwater aquifers (ESCWA, 2005).

TABLE 1: DEPENDENCY INDICATORS

Data / Indicator	1	2	3	4	5	6	7	8	9	10	11	12	13
Per capita use of fresh water resources	476.2	980.2	2,364.9	161.3	203.1	456.2	606.5	89.8	330.0	1,046.4	992.7	900.8	161.8
Groundwater abstracted as a percentage of total water resources used (%)	72.5	10.6	1.7	64.8	89.4	15.5	77.7	71.7	92.5	65.7	56.0	76.1	65.4
Per capita use of fresh water resources (m^3/p/y)	476.2	980.2	2,364.9	161.3	203.1	456.2	606.5	89.8	330.0	1,046.4	992.7	900.8	161.8

1. Bahrain; 2. Egypt; 3. Iraq; 4. Jordan; 5. Kuwait; 6. Lebanon; 7. Oman; 8. Palestine; 9. Qatar; 10. Saudi Arabia; 11. Syria; 12. United Arab Emirates; 13. Yemen

TABLE 2: DEPENDENCY RATIO (MODIFIED FROM FAO, 2003)

Data / Indicator	1	2	3	4	5	6	7	8	9	10	11	12	13
ISWR (mcm)	4	500	34,000	400	0	4,100	900	70	1	2,200	4,800	200	4,000
IGWR (mcm)	0	1,300	1,200	500	0	3,200	1,000	730	50	2,200	4,200	100	1,500
ISWR-IGWR overlap (mcm)	0	0	0	200	0	2,500	900	0	0	2,000	2,000	100	1400
TIWR (mcm)	4	1,800	35,200	700	0	4,800	1,000	800	51	2,400	7,000	200	4,100
TEWR (mcm)	110	56,500	40,200	200	20	-400	0	10	2	0	19,300	0	0
TRWR (mcm)	114	58,300	75,400	900	20	4,400	1,000	810	53	2,400	26,300	200	4,100
DR (%)	96.5	96.9	53.3	22.2	100	0.0	0	1.2 (17.9)	3.8	0	73.4	0	0

1. Bahrain; 2. Egypt; 3. Iraq; 4. Jordan; 5. Kuwait; 6. Lebanon; 7. Oman; 8. Palestine; 9. Qatar; 10. Saudi Arabia; 11. Syria; 12. United Arab Emirates; 13. Yemen

(ISWR: internal surface water resources; IGWR: internal groundwater resources; TIWR: total internal water resources; TEWR: total external water resources; TRWT: total renewable water resources; DR: dependency ratio)

TABLE 3: SUSTAINABILITY INDICATORS

Indicator	**Unit**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Water use intensity	%	252.0	117.0	77.1	52.4	282.9	59.6	114.5	38.3	197.2	299.7	93.9	916.9	116.1
Water deficit	$m^3/p/y$	-287.2	-142.3	701.1	146.4	-131.3	309.0	-76.6	144.8	-162.7	-697.3	64.0	-802.6	-22.5
Water stress	100 p/unit flow	52.9	11.9	3.3	32.5	139.3	13.1	18.9	42.6	59.8	28.6	9.5	101.8	71.7

1: Bahrain; 2. Egypt; 3. Iraq; 4. Jordan; 5. Kuwait; 6. Lebanon; 7. Oman; 8. Palestine; 9. Qatar; 10. Saudi Arabia; 11. Syria; 12. United Arab Emirates; 13. Yemen

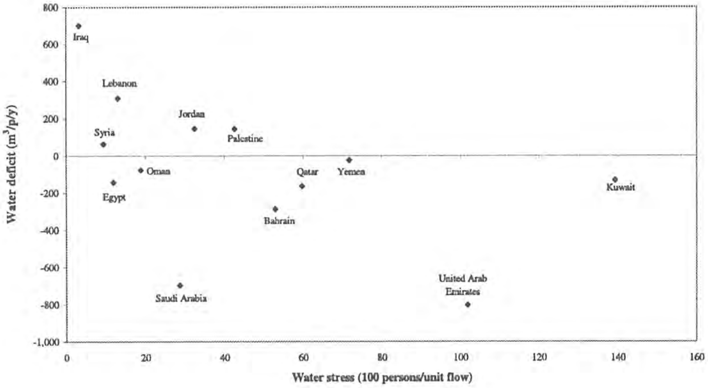
5.2 Sustainability

Three indicators are used for assessing sustainability of the available water resources: water use intensity, (ratio of per capita fresh water use to per capita fresh water resources); water deficit (the difference between per capita fresh water resources and per capita fresh water use); and water stress, defined as hundreds of persons per unit flow (one unit flow is one million m^3 of renewable water) arrived at by dividing 10,000 by per capita availability of fresh water.

The highest water use intensity (917%) is in the United Arab Emirates (Table 3) where it has already reached an order of magnitude higher than the maximum permissible limit for securing sustainability (i.e. where per capita use equals per capita share). High intensities are also observed in Bahrain (252%), Kuwait (283%) and Saudi Arabia (300%). Egypt, Oman, Syria and Yemen have intensity ratios within the range of the permissible limit or slightly higher. The per capita use of water in Iraq, Jordan, Lebanon and Palestine is still lower than the per capita share from available resources, with the lowest intensity currently prevailing in Palestine. When these intensities are translated to water deficit, we can see that Member States can be grouped into two categories: those with water deficit (Egypt, Kuwait, Oman, Palestine, Qatar, Saudi Arabia, United Arab Emirates and Yemen) and those without (Bahrain, Iraq, Lebanon, Jordan and Syria) as displayed in Figure 11. In terms of water stress, the Member States can be divided into 4 types:

- Countries with critical water stress (>10,000 persons/unit flow): Kuwait and United Arab Emirates
- Countries with serious water stress (5,000–10,000 persons/unit flow): Bahrain, Qatar and Yemen
- Countries with significant water stress (2,500-5,000 persons/unit flow): Jordan, Palestine and Saudi Arabia
- Countries with slight water stress (<2,500 persons/unit flow): Iraq, Egypt, Lebanon, Oman and Syria.

Figure 11: Water deficit vs.Water stress



6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Information on water resources in the ESCWA region is limited in scope

Water data and other related information available on the ESCWA countries have been analyzed to assess the status of water in each country and across the Region as a whole. Twenty-eight indicators have been identified and used for the assessment of water resources availability (7 indicators), land and water resources use (11 indicators), dependency and accessibility (8 indicators), and sustainability (3 indicators). Using the DPSIR approach (Driving forces for water use, Pressures, State, Impact, and Response), the current indicators can be broken down into 5D, 8P, 5S, and 11P. The fact that no indicators are available on the impact (I) of the present use on the society and/or ecosystem is alarming in the sense that the benefits of water use and its negative effects on the environment still remain obscure. In a predominantly arid and semi arid zone such as the ESCWA, a benefit to the society is often at the expense of the ecosystem because water resources are usually overexploited. Therefore, sustainable management of the available resources cannot be assessed without proper indicators for evaluating the impact of water use. Similarly, an integrated management of the resources requires indicators on the quality of water that are also not presently available for any of the ESCWA countries. Such indicators are important for monitoring groundwater quality since the most promising aquifers in the Region are vulnerable to quality deterioration because of their shallow water table and/or proximity to seawater. Many of the urban centers in the region have developed on shallow aquifers and hence are polluting these aquifers by surface and/or sub-surface effluent. Deeper aquifers that are usually of regional scale are also prone to salinization and quality deterioration due to mixing of various water bodies through fracture zones.

6.2 The absence of adequate data on the dependency of member States on shared water resources

A very significant portion of the freshwater from natural sources consumed in Bahrain (96.5%), Egypt (96.9%), Iraq (53.3%), Kuwait (100%) and Syria (73.4%) and, to a lesser extent, Jordan (22.2%), Palestine (1.2%) and Qatar (3.8%) (FAO, 2003), comes from outside the political boundaries of these countries. FAO data, suggests that Oman, Saudi Arabia, United Arab Emirates and Yemen have zero dependency on external water resources. This is not entirely true, however, since these countries depend to some extent on some of the most extensive aquifers in the Region. Unfortunately no data on dependency on shared water resources is presently collected by the Member States. The dependency on internationally shared water is particularly important for Egypt, Iraq and Syria because of the substantial volumes of water from external sources.

6.3 Most of the ESCWA region is presently under "water poverty" conditions

Several writers, who see "water crises" of varying magnitudes around the Arab world, take a water resource base of one thousand cubic meters available per capita per year (1000 m^3/p/y) to represent a "water barrier" below which nations and regions will become increasingly susceptible to various economic and social ills (Rogers and Lydon, 1993). It is furthermore estimated that the average water requirement for producing food and providing other basic needs in a modern society living in a typical semi-arid environment is circa 1350 m^3/p/y (SIWI, 2002). When the status of water in the ESCWA Member States is evaluated against this background and internationally accepted norms, it becomes clear that all countries, with the exception of Iraq and possibly Syria, are presently suffering from "water poverty" even when the supplementary volumes of water produced from non-conventional sources are considered. The situation is particularly serious in Jordan and Yemen where "water poverty" is compounded by low national capital income.

6.4 Only the GCC countries are able to produce enough water from non-conventional sources for alleviating the currently prevailing water poverty

Increased domestic water demand has made it necessary for some of ESCWA countries to augment their scarce natural water resources through non-conventional sources, mainly desalinated seawater/brackish groundwater, treated wastewater and agricultural drainage water. ESCWA region has, out of necessity, become a world leader in the production of desalinated water, which is primarily concentrated in the GCC countries. These countries produce significantly high volume of non-conventional water in comparison with other ESCWA countries. However, a significant difference can also be seen within the GCC countries. The total volume of water produced from non-conventional sources in Bahrain, Kuwait, Qatar and United Arab Emirates is significantly in excess of the total renewable water resources available for these countries. The volume of water produced in Bahrain from desalination and treated wastewater/ agricultural drainage is equivalent to the total water available to this country from natural conventional sources. The volume of water produced from non-conventional sources in the other 3 countries, as compared with conventional sources, is almost 2-3 times. These 4 GCC countries have become dependent mainly on desalination for most of their daily uses. The other 2 GCC countries (Oman and Saudi Arabia), however, are still dependent largely on renewable water resources despite the fact that Saudi Arabia produces close to 80% of all the water produced from non-conventional sources in the remaining 5 GCC countries.

6.5 Most of the available freshwater in the Region is being consumed in agricultural development that hardly contributes to national economies

The bulk of the water used in the ESCWA region goes to agricultural development. Agricultural water requirement, which was estimated at123.3 billion cubic meter (bcm) and 136.5 bcm in 1990 and 1997 respectively, has now increased to 146 bcm (ESCWA, 2003). Agricultural water demand is in excess of 50% of total water use in all ESCWA countries except Kuwait and above 80% in 5 countries (Iraq, Oman, Saudi Arabia, Syria and Yemen). These countries are relatively abundant surface water from perennial rivers (Egypt, Iraq, and Syria) or seasonal flash floods (Oman, Saudi Arabia, and Yemen) and/or cultivable land use over 75% of their water in the agricultural sector. The economic return from agricultural development is generally very poor in most countries (<10%). Agricultural economic efficiency (agricultural GDP divided by agricultural work labor force) has been less than 1.0 since 1995 in all countries except Iraq and Lebanon. This means that productivity of the work force in the agricultural sector is very low, particularly in Egypt, Syria and Yemen where agricultural GDP is relatively high.

6.6. High water use intensities are hindering sustainability of the water resources in many ESCWA countries

Water use intensity, defined as the ratio of per capita fresh water use to per capita fresh water resources characterizes most of the ESCWA countries. The highest water use intensity (917%) is in the United Arab Emirates where it has already reached an order of magnitude higher than the maximum permissible limit for securing sustainability. High intensities are also observed in Bahrain (252%), Kuwait (283%) and Saudi Arabia (300%). Egypt, Oman, Syria and Yemen have intensity ratios within the range of permissible limit or slightly higher. When these intensities are translated to water deficit, the Member States can be grouped into two categories: those with water deficit (Egypt, Kuwait, Oman, Palestine, Qatar, Saudi Arabia, United Arab Emirates and Yemen) and those without (Bahrain, Iraq, Lebanon, Jordan and Syria). Of the countries with water deficit, the stress related to water use, in terms of the number of persons per unit flow, is especially serious in Yemen and Palestine.

In the light of the above, the following suggestions can be made:

1. The DPSIR (Driving forces for water use, Pressures, State, Impact, and Response) approach should be adopted and applied by all ESCWA countries to the analysis, updating and upgrading of available information such that a final set of data, including indicators and possibly indices, can be formulated and regularly updated.
2. Harmonization and exchange of data is to be observed by member States, through collaboration and coordination with ESCWA via its Committee of Water Resources (CWR).
3. Special attention is to be made by both ESCWA and member States on how to incorporate land and water use management in the national IWRM plans currently under preparation, and formulating a proper mechanism for data acquisition and quality control that would ensure implementation of these plans.
4. The low economic return from the agricultural sector needs to be addressed to improve the economic value of the scarce water resources in the region.
5. Water quality monitoring networks need to be established and upgraded in the region as many countries suffer from the lack of water quality information and indicators.

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Participation in ground water protection

Fatima Abdel Rahman Attia

PARTICIPATION IN GROUNDWATER PROTECTION

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ABSTRACT

One of the fundamentals of integrated water resources management is the involvement of all stakeholders and beneficiaries. As water is essential to all forms of life, competition for water among users is escalating as growing needs outstrip the limited resources. The objective should be to transform the competition between users and stakeholders into a form of cooperation that achieves the largest overall revenue with the least sectoral harm. Groundwater protection aims at preventing non-beneficial uses of the resource and prevention of its degradation (quantitative and qualitative); leading to sustainable development of the resource base and activities based on it. A special case is non-renewable groundwater, where the word sustainability is not straightforward. Issues facing groundwater sustainability are not only technical but extend to cover institutional, awareness and legislative aspects. The introduction and application of appropriate approaches both in the socio-economic, legal and scientific areas are therefore prerequisites for the management and rational use of groundwater. The key is the participation of stakeholders and beneficiaries. Participation of beneficiaries/users is not new in our communities. An example is the style of groundwater management in the oases which can be considered an integrated management system, based on participation of the whole community, equitable use of the resource, and the environmental and physical conditions. Of interest is that women have got their right to water (inherited or share) according to Islamic Sharia.

The questions here are:

1. Do we make use of indigenous systems of participatory groundwater management or copy from other communities?
2. At what management level(s) do we involve beneficiaries?
3. What form(s) of organizations are suitable under the present set up of mixed water uses and mixed categories?

The paper tries to respond to the previous questions, based on experiences carried out in Egypt

INTRODUCTION

Participation-An Important element of IWRM

Participation is the act of participating or having a share in or taking part in or share in (an action or property, etc.).The main objective of integrated water resources management (IWRM) is to achieve sustainability in water resources for current and future generations. IWRM focuses on three major aspects: supply management, demand management, and water quality management. Sustainability of water resources, on the other hand, is achieved through the adoption of a package of structural (hardware) and non-structural (software) actions.

- Supply management aims at developing available water resources and reducing operational losses. It focuses on the optimal use and allocation of resources of different qualities according to types of requirements.
- Demand management aims at implementing actions and strategies for the reduction of demands and optimization of water use. Changes of cropping pattern and application of modern irrigation techniques are measures for the reduction of demands.
- Neither the supply side nor the demand side of the management style can be implemented without a full consideration of users and the environment. Planners have to realize that cultural and socio-economic aspects play an important role in the success of actions; being it structural or non-structural.

> One of the fundamentals of integrated water resources management is the involvement of all stakeholders and beneficiaries.
>
> As water is essential to all forms of life, competition for water among users is escalating as growing needs outstrip the limited resources.
>
> The objective should be to transform the competition between stakeholders into a form of cooperation that achieves the largest overall revenue with the least sectoral harm.

The Need for Groundwater Protection

> The word protection can be defined as the preservation from loss, waste or harm.
>
> Groundwater protection would thus mean prevention of non-beneficial uses of the resource and prevention of its degradation (quantitative and qualitative)
>
> Leading to sustainable development of the resource base and based activities.

- Groundwater is the invisible component of the hydrologic cycle on earth.
- Its complicated characteristics and invisibility have resulted in a delayed knowledge base compared to surface water.
- The low velocity of groundwater movement may result in severe deterioration of the resource before it is detected.

Comparative Advantages	
Groundwater	**Surface Water**
Large storage capacity and large aerial extent	Small to moderate storage capacity (local)
Low flow velocity	Unrestricted velocity
Low vulnerability to pollution	High vulnerability to pollution
Large residence time	Small residence time
Extreme pollution persistence	Easy to clean
Constant temperature, increasing with depth	Variable temperature
Low evaporation losses	High evaporation losses

Characteristics of the Arab Region Pertinent to Groundwater Protection

The majority of the Arab countries has already approached full utilization of their available fresh water resources, and has or will soon face water stress. The present per capita share in fresh water resources varies from 73 to about 3,000 m^3. Options for developing additional fresh water resources are almost none. Most surface water resources have been developed and fully allocated to demands. The same applies to accessible renewable fresh groundwater resources in the majority of the countries. Some countries have already started to recycle water one of more times (Egypt, Tunisia, Libya, Bahrain).

> Although the potential of non-fresh groundwater in the region is expected to be huge, it not yet properly explored. This important source of water can play an important role in the near future.
>
> A proper assessment of the potential and management styles needs to be well identified prior to the utilization of such resource.

Most aquifer systems are considered highly vulnerable to pollution due to their nature (e.g. leaching capacity). If we add to the intrinsic vulnerability, the impact of recycling effluent from various uses, one would expect deterioration of available water resources in the near or mid term. In the absence of regulations and their enforcement, monitoring and evaluation systems, the condition will degrade, resulting in severe problems that may be irreversible.

Main Issues Facing Groundwater Sustainability

Issues facing groundwater sustainability are not only technical but extend to cover institutional, awareness and legislative aspects.

- Because agriculture is the largest economic activity, it withdraws the major portion of groundwater; and, in return, it results in groundwater pollution. Protection of drinking wells (well proper) from agro-chemicals is very difficult.
- The lack of comprehensive monitoring (early warning) and enforcement of legislation is adversely affecting the sustainability of groundwater.

Table 1: Main issues facing groundwater sustainability

Aspects	Resulting Issues
Institutional (e.g. fragmentation of plans)	Poor allocation of water resources among sectors and poor land and water use
	Loss of wetlands, springs, etc.
	Overexploitation, increased cost of groundwater, loss of investments
Technical (e.g. lack of monitoring, poor recycling of effluent)	Poor protection of groundwater and water wells
	Deterioration of groundwater quality
Awareness (e.g. poor understanding of deterioration mechanisms)	Wastage of groundwater (flowing wells)
	Groundwater pollution from various sources
	Excessive pumpage resulting in saline intrusion/upcoming
Legislative (e.g. water rights, licensing)	Depletion of resources and loss of investments
	Loss of water rights
	Increased pumping cost

- Due to the shortage of fresh water, agricultural and domestic drainage water is being recycled irrespective of the adverse impact on groundwater, especially in the rural areas where shallow groundwater is the main source of potable water.
- Both decision makers and the public lack the proper understanding of degradation mechanisms, resulting in a continuous degradation of this precious resource.
- Under some hydrogeologic conditions (i.e. artesian pressure), groundwater can be free flowing. If wells are uncontrolled or poorly controlled, this results in water wastage and deterioration as well as inundation of agricultural lands.

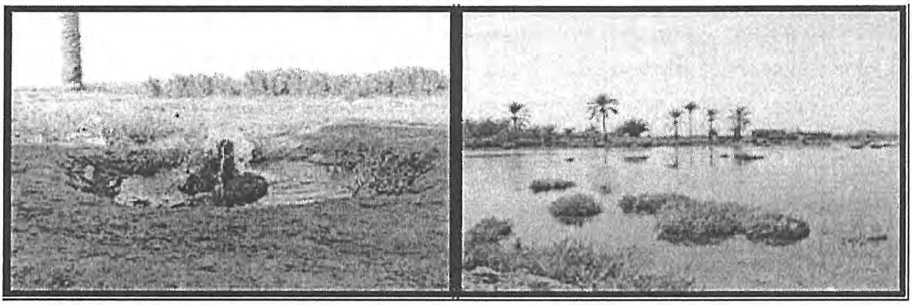


Figure 1: A flowing uncontrolled well resulting in water wastage and loss of agriculture

> **The introduction and application of appropriate approaches both in the socio-economic, legal and scientific areas are therefore prerequisites for the management and rational use of groundwater**
>
> **The key is participation**

PARTICIPATION FOR GROUNDWATER PROTECTION-THE INDIGENOUS EXPERIENCE IN THE EGYPTIAN OASES

Water in the Oases

- The inhabitants of the oases consist of groups of Tribes emigrated from the Arab Peninsula in the old times or, recently, from nearby cities of the Nile valley and delta.
- Irrespective of the historical changes in the environment, the inhabitants still keep their culture.
- Water plays an important role in the distribution and settlement of oases inhabitants as well as in their life. People used to settle around springs and dug boreholes to increase water availability.
- Water is considered the source of power and economy of the community and not the land.
- Water is sold, traded and rented independent from the land. For this reason, the tribes have developed strict regulations to ensure water rights and equitable allocation of the water resources.
- Water resources (water points) and water rights are inherited in the family/tribe.

Traditional Regulatory Framework

Prior to any decision on drilling a new water point, the heads of families (beneficiaries) involved meet to discuss all actions, leading to the following:

> The natives have developed their own framework to regulate groundwater development and use.
> The framework consists of various steps, namely agreement, implementation and supervision, development and follow up and evaluation.

- ❑ An agreement on the location (selection is based on their experience);
- ❑ Distribution of shares, roles and cost (money, efforts, animals or crops);
- ❑ Selection of professional labors;
- ❑ Election/selection of chair person (Ohda), who is normally the one holding the highest share and/or has high experience in the work. The Ohda becomes responsible afterwards on the activities and distribution of water shares.

> The Ohda plays a major role during the work implementation phase through:
>
> - Collection and documentation of shares;
> - Administrative supervision of workers and their performance;
> - Technical supervision and follow up of works;
> - Supply of goods and equipment;
> - Solution of any conflict between the workers;
> - Heading the board for solution of big conflicts and problems that may arise during the implementation.

Figure 2: Well Development (left); and Fixation of Sand Dunes (right)

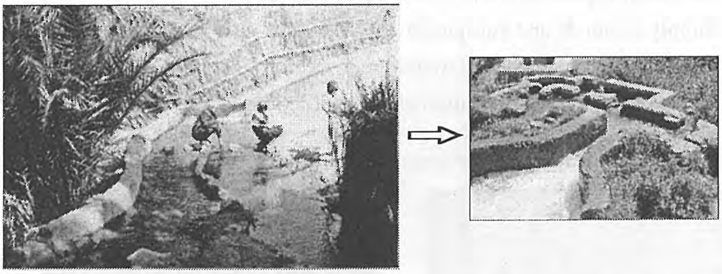
> - Land is distributed longitudinally, taking into consideration equity in land quality, water flow and topography.
> - Internally, the head of the family is responsible for the distribution of lands among members.
> - Each share holder starts by planting wind brakes to protect his land and water from moving sands and sand dunes.

- Follow up and evaluation are carried out to ensure proper performance of the water system, revise water allocation, agree on non-perennial crops, approve trading or selling of water shares/rights, solve conflicts and collect taxes (money or products).

Water Allocation

> Water allocation is based on original shares, regulated by the Ohda.
> However, if the water flow is reduced due to any reason, shares are also reduced with the same ratio until an action is taken.

- Irrigation is distributed over 24 hours, to cope with the nature of groundwater flow (continuous) and to eliminate wastage.
- The main indicator for irrigation amounts is the flow rate of the water point and the time taken for irrigation (this is the location of the sun during daytime and the moon during night time).
- The water given to fields is adjusted with the help of a wooden distributor which consists of a wooden block prepared to satisfy the water shares at each water point.



- Water is diverted to the land every 7 days in the summer and every 12 days in the winter.
- Beneficiaries may organize themselves into groups (collective irrigation) to ensure equitable use of water.
- Each group decides on night and day irrigation each time they receive the water.

Historical Development of Legislation

> Ownership in the oases is based on historical heritage of shares.
> However, water rights from springs are initially shared by all inhabitants.
> To protect water from any misuse along with ensuring the continuity of settlements and settlers' activities, the government has initiated legislations

- The Old Civil Law (1867): It gives the right of land ownership to those who cultivated the land. Rights may be lost if the land is left unused for 5 successive years.
- The New Egyptian Civil Law (1948): It states that, if an Egyptian cultivates bare land, it becomes his own even if he does not obtain a license. But he might loose this ownership if he leaves the land bare for 5 successive years within a 15 years period.

- ➢ Law No. 100 (1964): This has been a result of the changing conditions of water resources in the desert areas. It states that in the case of lands that have been cultivated for at least one year, but stopped due to wells deterioration or malfunctioning, land owners can be compensated by similar pieces of land in the areas developed by the Government. It also states that the minister can take the land back from any owner for the seek of the general public (nation).
- ➢ Presidential decree No. 512 (1993): It states that every owner of land that used to be irrigated from flowing wells and springs (before 1961), has the right to be compensated with a piece of land, based on the his previous water right (either at the initial stage or the year 1961, which ever is larger.

Water Rights and Water Trade in the Oases

Water in the Oases has historically been considered a good. Thus it can be traded and sold There are a number of agreements that have prevailed and agreed upon in buying and selling water. Agreements are made in a religious ceremony.

- A family or one person can sell his water share following a contract (*Hugga*); which states the amount of water sold in terms of *kirat* or *sahm;* and the agreed upon price (money or gold), name of the water point and Ohda (chairman).
- The contract is signed by the Ohda and witnesses; then approved by the Mayor and official institutions.

Agreement

- It occurs between two owners, one who owns water exceeding his requirements and one experiencing water stress.
- This situation normally happens in the case of reduced flow from or complete stop of the water point.
- The regulation adapted in this situation is that the first (with water exceeding his requirements) irrigates the land of the second against 50% of the products.

Trade

- In some situation, water shares can be satisfied from more than one point. This is normally done to minimize the risk due to reduced flow from any source.
- Trading of sources can take place between share holders allowing one holder to use water from a nearby water point that belongs to another and letting the other use his share (an equivalent amount) from a water point located far from the first but close to the second cultivation.
- Both parties, however, keep the right to return back to their original water points.

Cultivation

- It gives the opportunity to a person who does not own a water right/share to cultivate the land of an owner against getting one third of the product.
- The owner supplies all types of seeds and fertilizers. He can also get a laborer to irrigate the date palm trees against getting one complete unit of the best date argons.

Gaalah

- This system gives the right to people who do not have any water share.
- They can apply for the rehabilitation of a water point that has stopped flowing against getting the right of half its flow.
- These are considered new share holders (Mugaelin) subject to conditions/agreement between them and the original share holders of the water point that has stopped (Mugaala).
- The priority is given to the original share holders of the water point, either through payment of rehabilitation cost or carrying out the work. They also get an additional share added to their original one.
- If the spring does not recover (returns back to its original flow), the Mugaelin do not get any right for payment or share.

Traditional Participatory Groundwater Management in the Egyptian Oases-Lessons Learnt

- Water management in the Egyptian Oases has been based on active cooperation among families and individuals (the whole community) through their efforts, expertise and payment.
- The oases inhabitants have been pioneers in giving shares to women, giving her also the right to inheriting (Al Sharia).
- Water management is based on several factors, namely:
  1. Equitable rights to water.
  2. Regulation of irrigation rotation among beneficiaries to prevent any conflict.
  3. Irrigation rotation and application rates are based on actual water requirements (deficits) and location of the fields.
  4. Prevention of water wastage to ensure its sustainability and the sustainability of their lives:
     - Construction of storage reservoirs for night or accidental storage (decreased flow).
     - Regulation of night irrigation.
  5. Appropriate citing of wells, normally close to good soils with minimum length of the water distribution system. This ensures minimum distribution water losses (seepage) and optimum use of system characteristics (i.e. aquifer acting as a distribution system).
  6. Utilization of natural materials such as pipes to deliver water through sand dunes.
  7. Giving irrigation gifts to irrigators who irrigate during feasts in addition to additional shares to first irrigators (in the morning) and to those whose land is situated at the tail end.
- The water management system in the oases can thus be considered an integrated management system, based on participation of the whole community, equitable use of the resource, and the environmental and physical conditions.

TOWARDS PARTICIPATION IN GROUNDWATER PROTECTION-POSSIBILITIES UNDER PRESENT CONDITIONS

Why not making use of the inherited systems? What modifications are needed?

Present Situation – Main Changes and Challenges

The world has changed considerably which dictates also changes in behaviors.

- The population has increased; while water and land resources remained unchanged, resulting in a critical percapita decrease in water and land shares.
- Recent climate change has affected several regions, resulting in less rainfall intensity (less effective rainfall) and increased evaporation.
- Technology development has encouraged (and helped) people to develop more water resources which was not possible in the past.
- The life style of people has changed dictating more percapita consumption.
- Pollution of surface water has resulted in more dependence on groundwater.

Adding to the previous reasons the delay in studies and investigation technologies related to groundwater management, the result is a quick degradation of this precious resource, especially in the case of non-renewable groundwater.

> Construction of deep wells within the catchment's area of springs and shallow wells would result in the depletion of springs and shallow wells.

Future Perspectives for the Participation in Groundwater Protection

Groundwater protection dictates a balanced address of technological (equipment), policy and institutional aspects.

- The technological aspects form the hard core of protection. Criteria should thus be set confirming:

    1) The appropriateness of the technologies in terms of simplicity and cost (initial and running);

    2) Flexibility and response to users' needs; and

    3) Capability to be adapted to future needs.

- Introduction of new technologies should also consider users' acceptance and sustainability of technologies.
- Future policies and planning should focus on the basin scale and regions, recognizing possible significant changes which could impact adversely on the already disadvantaged groups.
- Special attention would have to be given to preparing people for changes and having them participate (mainly through representative bodies) in decisions.
- An identification of participation level is important to ensure sustainability of the resource base.

SCALES OF PARTICIPATION-WATER MANAGEMENT SCALES

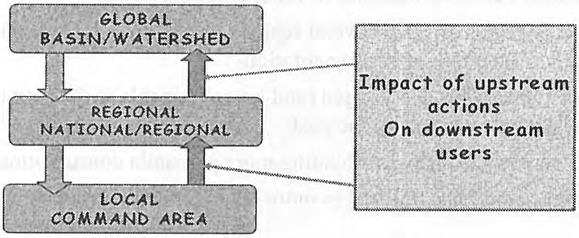


Table 2: Groundwater management levels and involvement of beneficiaries

GW management level	Beneficiaries	Involvement
Well	Individual	- sharing in citing - investment and O & M
	Individuals or groups	- ***sharing in citing***
	Public (community or government)	- ***investment and O & M*** - ***shared decision and cost***
Well field	Individuals or groups	- *sharing in decision of layout*
	Community	- *Full cost, including studies, implementation, O & M and monitoring and evaluation*
	Government (industries, drinking, etc.)	
Hydrologic Basin	All communities and users within the basin	***Full involvement of representatives of communities and users in all steps of the project cycle***

- the italic blue dictates formation of Water Users'Organizations prior to any action.

➢ A mix of beneficiaries can be expected which might have a negative impact on small beneficiaries. This needs appropriate planning at the early stages of development to ensure equity in resource allocation and cooperation of the mixed community. Figure 3 illustrates a possible constitution of a water users' organization on district level (the smallest hydraulic unit).

> In one of the oases in Egypt, investors formed a sort of unofficial users' organization on the sub-basin level to ensure appropriate groundwater management technologies.
> Small beneficiaries in the oasis decided to join to benefit from the experiences of the investors, especially in marketing

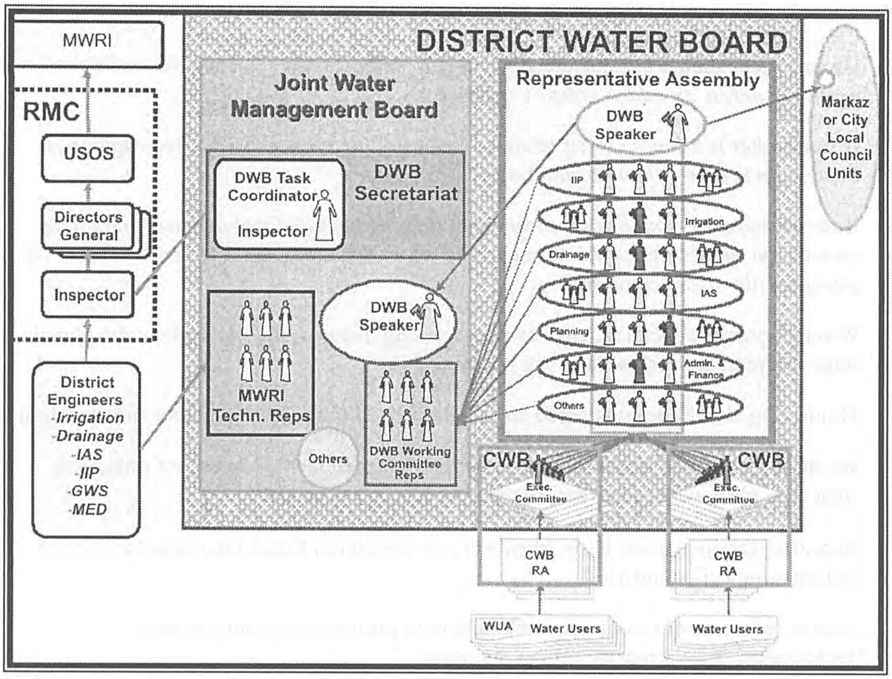


Figure 3: Structure of a water board on district level

> A Water Board is an organization consisting of and led by users of the water resources within a hydraulic unit. It involves interests of all water users and cooperate closely with water institutions (government and NGOs)

➢ However, prior to the initiation of any participatory scheme, various actions need to be taken, including:

1) Proper survey of existing conditions and understanding of the old communities culture and management styles.

> We need to know:
> 1. Why such a water management style has been used?
> 2. Distribution of roles and cost sharing?
> 3. What are the suitable technologies?
> 4. Can we modify the present set-up without harming the environment?

2) Identification of appropriate levels of participation, based on users' capacity and readiness.
3) Identification of communities' needs.
4) Preparation of institutions to take share in planning and interact actively with researchers and policy/decision makers.
5) Ensure appropriate representation of users' categories, including large investors and small beneficiaries.
6) Never copy. There are no blue prints.

CONCLUSIONS AND RECOMMENDATIONS-LESSONS LEARNT

- Groundwater should be considered a strategic water resource... *It should not be exploited unless an added value is ensured.*

- Groundwater is a fragile water resource, once polluted it is almost unrecoverable ... *Protection is easier than remediation.*

- *Water resources (groundwater in specific) development and management should be carried out in the framework of integrated water resources management to ensure the sustainability of developments.*

- Water resources allocation, e.g. resources among users, should be made at the planning stage in the framework of land use planning.

- Monitoring should be considered an integral part of the project cycle for timely action.

- We should not try to invent high cost and complicated technologies; but rather use what is in place with minor modifications whenever possible.

- Decentralization is a key issue. However, we should not forget the characteristics of hydrogeological boundaries.

- Human resources development, including both professionals and operators (technicians) should receive proper attention.

- Awareness is an important factor in the success of actions. It should not be restricted to the normal public, but should also extend to the decision makers.

- Enforcement of water protection legislation, and especially groundwater protection laws, should be given high attention.

- At the top of all the previous, the participation of users of groundwater is a major concern. It should be ensured prior to the decision on any new scheme and all over the project cycle. We should not forget the role of women (professionals or users) in protecting groundwater.

Groundwater Vulnerability Mapping:
An effective tool for preventing Groundwater pollution

Abdullah Droubi and Manfred Hobler

GROUNDWATER VULNERABILITY MAPPING: AN EFFECTIVE TOOL FOR PREVENTING GROUNDWATER POLLUTION

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ABSTRACT

Groundwater is a vital natural resource for a reliable and economic water supply in most of the Arab countries. Aquifers in most of the Arab region are experiencing an increasing thereat of over pumping and pollution. High population growth rates, urbanization, agricultural activities and industrial development are the main reasons for the rapidly increasing water demand, over pumping and pollution problems. In many cases, this unsustainable development not only led to the depletion of aquifers but also had disastrous effects on the water quality and the environment. The costs for groundwater rehabilitation are often prohibitive. Groundwater protection therefore becomes more and more important in order to prevent or minimize such problems. This paper presents the output and results of the investigations on soil and groundwater contamination in two pilot areas in Syria and Lebanon using the concept of groundwater vulnerability mapping.

Keywords: Vulnerability Assessment, Mapping, Groundwater Pollution, Case Studies, Syria, Lebanon

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***** Federal Institute for Geosciences & Natural Resources (BGR)- Germany***

I - Introduction

Due to the scarcity of Since surface water is scarce in the Arab region, groundwater has becomes the principal source of water supply. High population growth rates, urbanization, agriculture activities and industrial development are the main reasons for the rapidly increasing water demand. As water demand increases stresses on groundwater systems increase. Over pumping, groundwater quality deterioration and pollution problems are some of the impacts of such accelerated development. A disastrous effects on the groundwater quality and the environment have been observed in many Arab countries.

Groundwater pollution takes generally many years to show up in the withdrawn water withdrawn. By that time, it may be too late to prevent serious contamination. The costs for groundwater rehabilitation are often prohibitive and cost for groundwater rehabilitation is often prohibitive and requires even it takes long time . The reasons for that are (i) its relative in-accessibility, (ii)its large huge volume, and(iii) its slow flow rates.

Responsible of groundwaterGroundwater development has to take into account the long-term impact on the aquifer, the water quality, and the environment into consideration. As a result O,once a pollutant enters a groundwater aquifer, the environmental damage can be severe and long- lasting. Groundwater protection therefore becomes more and more important in order to minimize such risks and problems.

Groundwater vulnerability mapping is considered as promising technique for preventing pollution of aquifers. Since the Ggroundwater vulnerability to contamination is defined as the tendency or likelihood for contaminants to reach the groundwater system. Hence, , so it is a function not only of the properties of the groundwater flow system, but also of the proximity of contaminant sources, ,characteristics of the un-saturated zone, and other factors that can potentially increase loads of specific contaminants to the aquifer .

2. The Concept of Groundwater Vulnerability

The concept of groundwater vulnerability is based on the assumption that the physical environment may provide some degree of protection to groundwater against the natural and human impacts, especially with regards to contaminants entering the subsurface environment.

2.1. -1 Definitions

Intrinsic (or natural) Vulnerability: Vulnerability is an intrinsic property of a groundwater system that depends on the sensitivity of that system to human and/or natural impacts.

Specific (or integrated) Vulnerability: Potential impacts of specific land uses and contaminants, which may prove detrimental -in space and time to the present or future uses of the groundwater resource.

Groundwater Vulnerability Maps:

Groundwater vulnerability maps belong to the category of special-purpose environmental maps. They are classified as interpretive groundwater protection maps, derived from general Hydrogeological maps.

Assessment of Groundwater Vulnerability:

Vulnerability of groundwater is a relative, non-measurable, dimensionless property. The accuracy of vulnerability assessment depends above all on the amount and quality of representative and reliable data.

2.2. Basis for a Comprehensive Protection and Control Ssystem

- Development of adequate land use planning
- Establishment of protection zones
- Operation of monitoring systems
- Reasonable exploitation of the water resources
- Improvements in the storage, handling and disposal of polluting substances
- Awareness for environmental problems.

Mapping of groundwater vulnerability to contamination and of the regional pollution hazards can contribute significantly to reach these goals. Groundwater vulnerability mapping is helpful for:

GW Vulnerability Mapping is Helpful for

- Development of groundwater protection strategies (demonstrating needs for or consequences of actions)
- Regional land use planning: assignment of acceptable uses (zoning), search for suitable sites (screening), and identifying areas for use restrictions.
- Assessment of the potential impact of land use alterations on GW contamination.
- Setting priorities for GW monitoring and detailed studies.
- Setting priorities for measures such as soil redemption.
- Increasing the awareness of authorities and the public on issues of GW protection.
- Communicating decisions related to GW protection to affected groups.

Current practices in groundwater protection are based on a diagnostic approach, which takes the entire aquifer system with the overlying unsaturated strata and the soils into consideration and includes risk assessments, monitoring and legal aspects.

Groundwater vulnerability mapping has proven to be a valuable tool for land-use planning under aspects of groundwater protection. Within the framework of the ACSAD - BGR Technical Cooperation Project “Management, Protection and Sustainable Use of Water and Soil Resources in the Arab Region”, groundwater vulnerability mapping has been carried out in pilot areas in Syria and Lebanon. Over the last decades numerous methods have been developed to delineate areas where groundwater is highly vulnerable to pollution from areas where it is less vulnerable. After a review of the available database and some initial tests, a method has been selected, which has been developed by the State Geological Surveys of Germany. This method has also been applied in some pilot areas in Jordan in a cooperation project of the BGR with the Ministry of Water and Irrigation.

Overhead 1 (in the paper there are no overheads, figures only!!) shows some common definitions of groundwater vulnerability. According to VRBA & ZAPOROZEC (1994) groundwater vulnerability shows the tendency or likelihood for contaminants to reach the groundwater system after introduction at some location above the uppermost aquifer. In the ACSAD/BGR cooperation project we took oonly the intrinsic vulnerability, not the specific vulnerability (the vulnerability of the groundwater to a particular contaminant) was taken into consideration.

Groundwater vulnerability is closely related to risk assessment. For the evaluation of the overall risk of groundwater pollution, the groundwater vulnerability assessment has to be combined with an assessment of hazards. The risk of contamination can be defined as:

RISK = HAZARD * PROBABILITY.

This means that there is a high risk, if the source of contamination in the unsaturated zone/ soil surface occurs in an area of high vulnerability. Even in highly vulnerable areas, however, the risk is low if there are no sources of contaminants.

3. Groundwater Vulnerability Mapping

3.1. Protective Effectiveness of the Soil and Rock Cover

Attenuation of contaminants on their way through soils and the unsaturated zone to the groundwater depends on processes and mechanisms like retardation of absorbable pollutants, elimination of contaminants by chemical complexation or precipitation, biochemical transformation or degradation, evaporation of volatile compounds, and, especially in the saturated zone, dilution processes. Many publications deal with this subject (e.g.: FOSTER, 1988; VRBA & ZAPOROZEC, 1994). Soils play usually the most important role in the attenuation process. Due to the limited availability of oxygen, moisture and microbes, and the often lower cation exchange capacity these processes are normally less effective in the unsaturated zone. It should be kept in mind, however, that soils are often removed, especially in areas with rapidly progressing urbanisation, and thus completely loose their role in the attenuation of contaminants.

The protective effectiveness or filtering effect of the rock and soil cover depends to a large degree on the time for water and contaminants to reach the water table. Main factors are the thickness of the soil and rock cover above the saturated aquifer, the percolation rate and the velocity of the infiltrating water. Of special importance are tThe mineralogical composition of the rock cover, the degree of jointing and fracturing, the compactness and porosity of the rocks, the organic matter content, the pH values, and the cationic exchange capacity (CEC) are of special importance.

In this paper which representthis paper which represents the results of ACSAD - BGR Cooperation Project on sustainable development and management of groundwater and soil resources ,theresources, the mapping refers mostly to the intrinsic vulnerability of the groundwater. The assessment therefore concentrated on the main parameters, which determine the general protective effectiveness of the soil and rock cover. This approach has to be seen in connection with the project goals, the availability of basic data in the pilot areas and the time frame of the project. The possibility of assessing groundwater vulnerability in large areas at relatively low costs in a comparatively short amount of time, is the main advantage of such a simplification. This general assessment can be seen as a first important step to keep the risks of contaminating the groundwater resources under control, and to avoid situations where land use planning causes problems, which can hardly ever be corrected. Mapping of the intrinsic groundwater vulnerability forms the basis for future more specific investigations. Studies of the specific vulnerability could then be performed for particular purposes at a later stage in sensitive areas where groundwater pollution already exists or is expected to occur in the near future (BGR - WAJ, 1997).

3.2. Methodologies of Groundwater Vulnerability Mapping

Many mapping methods have been developed over the past two decades to delineate areas where groundwater is vulnerable to pollution from areas where it is less vulnerable. MARTIN (2000) lists the following main categories of methodological approaches:

Process Based Methods: include mathematical descriptions of physical, chemical and biological processes occurring in the unsaturated zone and in the aquifer. This approach involves mathematical modeling. Examples of practical applications, however, are still rather limited since the quality and reliability of available data is usually insufficient, especially for regional studies.

Statistical Methods: are applied to find relations between measurable parameters affecting groundwater vulnerability and measured groundwater quality (correlation analyses). Problems in the practical application arise from the requirement of large and regionally densely distributed data sets and from the assumption that areas of high vulnerability are reflected by high existing groundwater contamination.

Index And and Overlay Methods: are presently most important for practical purposes. In this procedure sets of maps are being prepared from which parameters for groundwater vulnerability assessments can be deducted by delineating zones of equal properties (e.g. rainfall, groundwater recharge, soil, geology, depth to groundwater table). Scores (points) or qualitative ratings are assigned to relevant attributes affecting groundwater vulnerability. The rating procedure results in a qualitative and relative assignment of vulnerability levels in different parts of the map. These maps are than combined in order to reach an overall rating.

Systems like DRASTIC (ALLER et al, 1985), GOD (FOSTER, 1987), SINTACS (CIVITA, 1988 &1990) and the rating system of the State Geological Surveys of Germany (HOELTING et al, 1995) belong to this group.-**DRASTIC** (Aller et al. 1985) represents the best known example. For this parametric point-count system model the following parameters have to be included into the evaluation: **D**epth to aquifer, **R**echarge, **A**quifer media, **S**oil media, **T**opography, **I**mpact of vadose zone, and **C**onductivity of Aquifer.

Each parameter is rated from 1 to 10. In addition, a weight factor from 1 to 5 is assigned to each parameter in order to account for different levels of impact. Differing weights have been assigned for the normal and the agricultural DRASTIC. The rating for the listed parameters can be determined according to the tables and graphs presented in the DRASTIC manual. The selection of parameter ratings (R) and weight factors (W) in a specific setting is left to the user's expert judgment. Weighted parameters are summed up to get the DRASTIC INDEX according to the pollution potential formula:

$$\text{Pollution Potential} = D_R{*}D_W+R_R{*}R_W+A_R{*}A_W+S_R{*}S_W+T_R{*}T_W+I_R{*}I_W+C_R{*}C_W$$

Based on a review of the different systems of groundwater vulnerability mapping, the **APPROACH OF THE STATE GEOLOGICAL SURVEYS OF GERMANY** (HOELTING et al. 1995) has been applied for the vulnerability mapping in the Damascus Ghouta Plain. The decision was mainly based on the positive experience with the application of this methodology under similar climatic conditions in Jordan (BGR - WAJ, 1997 & 1999) and other countries. It was also felt that the German method was the most suitable one to deal with the partly rather limited availability of basic data in large parts of the pilot area. This refers first of all to descriptions of the sedimentary strata in the unsaturated zone. Though the density of water wells is extremely high (some estimates go as high as thirty- to forty thousand wells), detailed lithologic descriptions of borehole cuttings are an exception.

The German approach represents a parametric point count system in which the intrinsic vulnerability rating is based on the approximate travel time of percolating water to the groundwater table. The overall protective effectiveness of the soil and rock cover increases with the number of points assigned to a particular area and has been subdivided into 5 classes. These classes range from very low (< 500 points; residence time of the percolating water up to about 1 year) to very high (> 4000 points; residence time of the percolating water > 25 years). Only vertical diffuse percolation of contaminants, not preferential flow or (sub-) surface lateral flow is taken into account.

The mapping procedure involves the preparation of maps from which the following parameters for the groundwater vulnerability assessment can be deducted:

W Factor for rating the **groundwater recharge rate** (ranges between 0.5 and 1.75, respectively 2.25 for arid areas with very low recharge rates)

S **Soil** down to a depth of 1m: rating of the effective field capacity (SeFC in mm down to a depth of 1m; scores between 10 and 750 points)

R **Rock type** (unsaturated zone only; up to 500 points per meter)
Unconsolidated Rocks (Rating of cation exchange capacity of rock)
Consolidated Rocks (Rating of permeability and fracture characteristics)

T **Thickness** of each layer in meters

QM Bonus points for visibly elevated **organic matter** content (75 points per m)

Q Bonus points for **perched aquifer** systems (500 points)

HP Bonus points for **artesian aquifer** conditions (1500 points).

The **total protective effectiveness (P_T)** is calculated using the formula:

$$P_T = P_1 + P_2 + QM + Q + HP$$

where

P_1 - protective effectiveness of the soil cover: **P_1** = S * W

P_2 - protective effectiveness of the rock cover:

P_2 $= W * (R_1*T_1 + R_2*T_2 + ... + R_n*T_n)$.

For the determination of P_2, it has to be distinguished between unconsolidated and solid rocks. For the first group the cation exchange capacity of the rocks is used as a measurement for the proportion of fine material and hence the residence time of percolating water. For the assessment of consolidated rocks, the product of points for rock type and a factor describing the degree of fracturing or the presence of karst phenomena is used. As for the soils, the rating of P_2 for each rock layer has to be multiplied with its thickness in meters and with the factor W (see above formula).

Zones of equal properties are elaborated on each thematic map and scores (points) are assigned to those areas (T table 1). The maps are thean combined and the total scores for each area are calculated. The process of calculating the overall protective effectiveness for the entire study area is complex and can best be achieved by the use of a Geographic Information System (GIS; e.g., ARC/INFO or a similar software system). The methodology has been described in detail by HOELTING et al (1995).

Table 1. Classes of overall protective effectiveness of the soil and rock cover and corresponding residence time of percolating water in the unsaturated zone (after HOELTING et al, 1995)

Overall protective effectiveness	Total number of points	Approximate residence time in the unsaturated zone
Very high	≥ 4000	> 25 years
High	2000 – 3999	10-25 years
Moderate	1000 – 1999	3-10 years
Low	500 – 999	several months to about 3 years
Very low	< 500	a few days to about one year, in karstic rocks often less

The main Reasons for Applying the German Methodology are:

- Use of fairly simple and straight forward methods in order to get results within a reasonable time period
- Use of easily accessible existing data in order to avoid, as much as possible, time consuming and cost intensive additional investigations
- Not to get involved in scientific details and problems, which are of secondary importance for the purpose of the map and often cannot be solved anyway because of an insufficient and sometimes unreliable data base
- Adaptability of the existing mapping approaches to the local situation
- Presentation of results in such a way that they can be used by none-specialists.
- Calculation of the overall protective effectiveness (PT)

$$\mathbf{P_T = P_1 + P_2 + Q + HP}$$

where ;

P_1 - protective effectiveness of the soil cover :

$P_1 = S * W$

P_2 - protective effectiveness of the rock cover :

$P_2 = W * (R_1 * T_1 + R_2 * T_2 + ... + R_n * T_n)$

W Factor for rating the **groundwater recharge rate**

S **Soil**: rating of the effective field capacity (to a depth of 1m)

R **Rock type** (unsaturated zone only)

- **Unconsolidated Rocks** (cation exchange capacity of rock)
- **Consolidated Rocks** (permeability, fracture characteristics)

T **Thickness** of each layer in meters

Q Bonus points for **perched aquifer** systems (500 points)

HP Bonus points for **artesian aquifer** conditions (1500 points).

Determination of the degree of vulnerability ;

Protective effectiveness of the soil is calculated as:

$$P_1 = S * W$$

where

S is the : effective field capacity of the soil (Table 2). (Rating for different classes of effective field capacity (SeFC) are in mm down to 1 m depth; and **W is** the percolation rate factor

W is the percolation rate factor

Table 2. Classification used for the soil factor (S)

Σ eFC [mm] down to 1 m	soil factor (S)
> 250	750
200 – 249	500
140 – 199	250
90 – 139	125
50 – 89	50
< 50	10

4. Applications of the Concept of Groundwater Vulnerability Mapping

4.1. Case Study 1: , Damascus - Ghouta Area , Syria .

The Damascus Ghouta Plain is located between longitudes 360 15' E and 360 39' E and latitudes 330 23' N and 330 37' N (F figure.1). It reaches from Damascus City, capital of Syria in the west to Lake Ateibeh in the east and from Adra City in the north, to a range of hills in the south (Jebel Abou Aatreez in the southwest and the volcanic cones of Dirat Al-Talloul southeast of the study area). The area includes most of the agricultural area and its surroundings east and south of the city. It covers an area of about 850 km2 if the mountainous hard rock area northwest of the city is excluded. There, the vulnerability of the groundwater to contamination has not been studied yet in detail. Comprehensive studies of the present status of soil contamination and soil vulnerability have been carried out in a somewhat smaller area of about 100 km^2.

Urban development is spreading rapidly in the Damascus area and the total population of Damascus and the Ghouta now exceeds 5 million. The land use map shows the intensity of horticultural and agricultural activities in the Ghouta plain (Figure fig.2). The growth of urban areas and settlements between 1990 and 2002 shows that the land cover has deteriorated by 30% (Figure fig.3). Due to the rapid population growth, migration from rural areas to the cities and intensification of agricultural activities, the water demand increased considerably in recent years. As indicated by the rapid decline of groundwater levels, present water consumption far exceeds natural replenishment. (Figure 4 fig .4).

Agriculture in the intensively cultivated Damascus Ghouta Plain is essential for the supply of agricultural products, such as fresh vegetables and fruits, meat and dairy products to the city. This greenbelt in the northeastern, eastern and southern surroundings of the city also plays an important role for the environment and the city climate. Groundwater abstraction in Damascus and the Ghouta plain contributes essentially to the domestic water supply of the city. In large parts of the Ghouta, the underlying aquifers represent the only source of water for irrigated agriculture and the domestic water supply of towns, villages and settlements. About 300 Million m3 of groundwater is used for agriculture, about 20 Million m3 for industry and 100 Million m3 for drinking water supply.

Rapidly increasing water demand, deteriorating groundwater recharge conditions and a succession of dry years led to severe over-pumping of the aquifers in the Ghouta in recent years. Springs and shallow wells dried up in many areas and the productivity of water wells decreased. Lack of water now seriously affects agricultural production, especially in the southern and eastern parts of the pilot area. Furthermore, most of the surface water is heavily polluted. Human activities like the disposal of untreated industrial effluents into rivers and channels, the use of polluted water for irrigation, uncontrolled garbage disposal and intensive use of fertilizers and pesticides endanger the quality of the groundwater.

Nowadays most of the wastewater of Damascus is pumped to a treatment plant in Adra, about 15 km northeast of the city. From there, the treated wastewater (about 80 million m3/ year) is pumped back to the northern and central part of the Ghouta. This situation led to an improvement of the quality of the irrigation water in part of the Ghouta and had considerable impact on the hydraulic regime, especially in the northern part of the project pilot area (Alrishan Adra area). However, the fundamental problem remains that a sustainable use of the ground-water resources seems impossible without substantial changes in the management and protection of the resources.

There is a considerable risk that some of the scarce water resources are being lost for domestic and even agricultural water supply due to pollution problems. Maps of groundwater vulnerability to pollution provide the necessary information for the protection of the groundwater resources and are suitable tools for planners and the concerned authorities to include aspects of groundwater protection in responsible land-use planning.

The preparation of the groundwater vulnerability mapping of the Damascus Ghouta (HOBLER et al, 2002) is based on the methodology, which has been developed by the State Geological Surveys of Germany. This work has been achieved within the cooperation project of ACSAD -BGR. The prepared map shows the intrinsic vulnerability of the groundwater. Characteristics and specific behavior of specific contaminants have been taken into consideration to a rather limited content only.

In the project, the evaluation of the groundwater vulnerability has been combined with studies of the vulnerability of the soils and the present status of soil contamination. Based on the pH-value, the clay content and the content of organic material, the vulnerability of the Ghouta soils (fig.5) can be generally classified as relatively low. However, areas of somewhat higher soil vulnerability have been delineated in the central part of the pilot area (from the Toura tributary in the Joubar - Erbeen area in the north to Koffer Batna, the Barada River and the area west of Mleha in the south). In large parts, these areas coincide with areas, where the protective effectiveness of the unsaturated zone above the aquifer is low to very low.

In large parts of the Damascus Ghouta, the protective effectiveness of the soil and rock cover above the saturated aquifer is high and the contamination of the groundwater by heavy metals and organic compounds still appears to be rather limited (Figures 6 & 7). At a few locations however, very high levels of heavy metals have been observed in the A horizon of the soil and there are clear indications that groundwater contamination problems could seriously effect the water supply situation in the near future. For example, in the tannery area at the eastern outskirts of the city, the hazards of groundwater pollution have to be considered as high to very high. Further, nitrate contents exceed the permissible values for drinking water considerably in many locations (Figure 8). Remediation of polluted aquifers is extremely costly and difficult, time consuming and sometimes practically impossible. Prevention of pollution, therefore, is much better than cure.

Waste disposal sites and uncontrolled handling of contaminating substances should be avoided by any means in areas of high groundwater vulnerability. Areas less sensitive to pollution can be taken into consideration as 'search areas' for the identification of suitable locations for hazardous activities. Due to uncertainties in the assessment process the map cannot replace detailed hydrogeological and geo-technical studies, which would include environmental impact assessments for a particular site.

Jurassic and Cretaceous limestones and Paleocene conglomerates in the adjacent mountain ranges west to north of the city are productive aquifers, which are important for local water supply and probably form part of the groundwater recharge system to the Ghouta Plain in some areas (Figure 9). Outcrop areas of these aquifers, particularly the limestones, offer little protection from contamination and should therefore be seen as high-risk areas. Use of abandoned limestone quarries for garbage disposal poses an enormous threat to the groundwater and should be stopped immediately (e.g. El Tal waste disposal site).

Concerns about water pollution and environmental problems are increasing in the relevant governmental institutions and in the population. Efforts however, to actively protect the groundwater resources are still insufficient.

Mapping Procedures for the Groundwater Vulnerability Map of the Damascus Ghouta Plain

The preparation of the map of groundwater vulnerability to contamination follows the procedure described in HOELTING (1995). The mapping technique is based on a rating system representing important factors, which determine the travel time of contaminants from the land surface to the water table. The higher the scores assigned to a particular area, the higher the protective effectiveness of the soil and rock cover. The assessment of the different parameters for the groundwater vulnerability mapping in the Ghouta Plain is explained in the following:

Rating for the percolation rate (W): The amount of water infiltrating per unit time is an indication for the residence time of the percolating water in the soil and rock cover above the saturated aquifer. If the percolation rate is high, a rapid downward movement of the (probably contaminated) water has to be assumed. High percolation rates therefore reflect a low protective effectiveness of the soil and rock cover.

The applied methodology of vulnerability mapping was developed in Germany where recharge is comparatively high. Accordingly, percolation rates between > 400 mm/a and <100 mm/a have been taken into consideration for the determination of factor W (values between 0.5 and 1.75; see Table 3). In order to adapt the German method to the low groundwater recharge rates in dry areas, a modified scale for the assessment of the percolation rate has been introduced for groundwater vulnerability mapping in Jordan (MARGANE et al, 1997). These modifications of factor W have also been used in the vulnerability mapping for the Ghouta area (Table 3).

According to the German methodology, the protective effectiveness is assessed on the basis of the assumption that the sole source of percolating water is rainfall. Under the conditions in the Ghouta, other sources, especially irrigation water losses, have also to be taken into consideration. The spatial distribution of factor W in the Ghouta pilot area is based on the following assumptions:

Table 3. Classification used for the Percolation rate factor (W)

Groundwater recharge [mm/a]	P-ET$_p$ [mm/a]	Percolation rate factor (W)
< 25		2.25
25 –49		2.0
50 – 99		1.75
100 – 199		1.5
200 – 299	100 – 199	1.25
300 – 399	200 – 299	1.0
≥ 400	300 – 399	0.75
	≥ 400	0.5

Factors between 1.00 and 2.25 have been proposed for the study area. Since the scores resulting from the assessment of the protective effectiveness of the soil and the rock cover are multiplied with the factor W, the total number of points is increased in large parts of the Damascus Ghouta. These higher scores indicate that the low recharge rates partly reduce the risk of groundwater contamination.

For the assessment of the effective protectiveness of the soil cover (S) the effective field capacity of the soils is used In the German methodology (eFC in mm/m). In the calculation, the eFC value of each individual soil horizon is categorised according to standard tables. After allocating the corresponding point numbers (S), the values are multiplied by their thickness (in dm) and the point numbers for each soil horizon down to a depth of 1 m, the average rooting depth, are added up. The total score for parameter (S) ranges between 10 and 750 points (SeFC in mm down to a depth of 1m).

Soils in the agricultural central part of the Damascus Ghouta are remarkably uniform and can be characterised as clay loam to clay soils (Mueller et al, 2000). This includes by far the largest part of the project pilot area in the Ghouta. In the entire area, where well-developed soils exist, the effective field capacity of the soil down to a depth of 1m is in the range of 140 – 200 mm/m. For the assessment of the effective protectiveness of the soil cover, 250 points have therefore been allocated for factor (S). The scores for the total protective effectiveness of the soil cover are calculated by multiplying parameter (S) with factor (W) according to its spatial distribution in the study area.

For the assessment of the effective protectiveness of the rock cover, parameter (R), it was necessary to distinguish between unconsolidated and consolidated rocks.

In almost the entire project area the rock cover of the unsaturated zone consists of unconsolidated rocks. The rating for the protective effectiveness is based on the cation exchange capacity of each rock unit. Unfortunately the lithological descriptions of borehole cuttings are often rather poor or do not exist at all. In most areas the evaluation is based on the well log descriptions in SELKHOP-PROMEXPORT, 1987. The problem of partly large distances between observation points (up to several km) also adds to the uncertainties in the assessment process.

Based on the lithological descriptions, the cation exchange capacity of each unit was estimated according to standard lithological tables and numbers of points were allocated. The scores range between 5 and 500 points per meter bed thickness. In view of the uncertainties caused by the often poor lithological descriptions, rather conservative (low) scores were allocated in the respective areas, since overestimation of the protective effectiveness of the rock cover could contribute to a false sense of security.

For the determination of the protective effectiveness of the consolidated rocks (RS) above the saturated aquifer, the formula: RS = O * F was applied. The values for the rock type (O), the structure characteristics (factor F; degree of faulting, jointing and karstification) and the total point numbers (RS) for the different units of consolidated rocks in the project pilot area shown in the table below. The total number of points ranges between 2 and 15 points per meter. The comparatively low scores are an indication of the low protective effectiveness of the consolidated rocks in the Ghouta pilot area (Table 4).

For the determination of the protective effectiveness of the rock layers above the saturated aquifer, the score of each layer is multiplied by its thickness in meters (factor T). The resulting scores of the different rock layers of the unsaturated zone are then summed up. Finally, the total score for the protective effectiveness of the unsaturated zone is calculated by multiplying the sum of the scores for the different rock layers with factor (W) according to its spatial distribution in the study area and adding the score for the soil cover.

Table 4. Allocation of Points for Rock Type (O), Structural Characteristics (F) and Total Points (R_s)

Rock type	O	F	R_S
Basalt	15	1	15
Marine limestone	5	0.4	2
Lacustrine limestone	5	0.5	2.5

The assessment of the spatial distribution of values for the thickness of the unsaturated zone is mainly based on a project map of 'Average Depth to Groundwater in the Damascus Ghouta'. Drilling records and water level measurements have also been taken into consideration (especially from monitoring wells). Since the thickness of the unsaturated zone plays such an important role in the assessment of the groundwater vulnerability, the map can only show the protective effectiveness of the unsaturated zone under the current conditions.

The depth to the groundwater table in the Damascus Plain is heavily influenced by human interference. Over-abstraction of groundwater led to high annual groundwater level fluctuations and caused a continuing drawdown of the water table of several meters in many areas. In view of the constantly increasing water demand and the deteriorating recharge conditions it is unlikely that the average depth to the groundwater table will decrease and that the thickness of the unsaturated zone will be reduced in the future. Only in the northern central part of the project pilot area where new areas are being irrigated (import of treated waste water), water losses are likely and the infiltration conditions are favorable, a rise of the water table is likely and indeed has been observed). In consequence, the protective effectiveness of the rock cover might decrease in the future in that area.

The situation in the project pilot area did not justify the assignment of bonus points for perched aquifer systems (Q). Bonus points for artesian aquifer conditions (HP) were not assigned in the project area, even though such conditions have been described for several areas. The reasons are that:

- the extent of these areas appears to be relatively small
- over-abstraction probably reduced the size of areas with artesian conditions because of the lowering of the piezometric head
- Artesian conditions are more common in deeper aquifers, which are only included in the vulnerability assessment if the overlying aquifers have been exhausted.

Local artesian conditions have therefore not been taken into consideration in the preparation of the vulnerability map. They provide, however, an additional safety factor for the protection of the groundwater in those parts of the aquifer system.

Regional Distribution of Aquifer Vulnerability

In respect to the regional distribution of aquifer vulnerability, the following aquiferous units have been taken into consideration because of their importance for the water supply:

- Unconsolidated Quaternary sand and gravel deposits in the Damascus Plain (most important aquifer in the pilot area)
- Limestone deposits in the surrounding mountain ranges
- Freshwater limestone deposits (especially in the eastern part of the pilot area)
- Basalt intrusions.

The regional distribution of the risk of groundwater contamination in the Damascus Ghouta is rather diverse and varies from very low to very high, as the groundwater vulnerability map shows (Figure 10).

The well-fractured and partly karstified limestone deposits in the mountain ranges west and north of Damascus are particularly vulnerable since groundwater recharge takes place through enlarged fractures with little filtration of pollutants. Flow rates in the underground might be very fast. Without more detailed investigations, the vulnerability of these areas can only be classified as very high. Any activities with the risk of contaminating the groundwater should be prohibited in this area. This also applies to the outcrops of basaltic rocks and freshwater limestones in the area south and east of Damascus, if a well-developed soil cover does not protect them.

The protective effectiveness of the soil and rock cover in the area along the Barada River and its surroundings in the central part of the Damascus Ghouta, has been classified as low to very low. This is mainly due to observations that the groundwater can be very close to the land surface and well permeable strata are quite common in this area. Unfortunately, some of the important industrial areas of Damascus are located in these high-risk areas (e.g. tanneries east of the old city).

Apart from the mentioned high-risk area in the central part of the Ghouta, the risk of groundwater contamination in the Damascus Plain has mostly been graded as moderate to low. The areas of very low risk of groundwater contamination are located in the easternmost part of the pilot area, along the slopes of the mountains south of Damascus and in the northeastern outskirts of the city. In those areas the thickness of the unsaturated zone is high and the permeability of the mostly clayey sediments is low. However, it has to be taken into consideration that those intercalations of sand and gravel could locally increase the risk of groundwater contamination.

In some parts of the study area, particularly in the east, the insufficient knowledge of the spatial distribution of freshwater limestone deposits is problematic. According to the available lithological information groundwater vulnerability in most of the area is low. However, if there are unknown occurrences of karstified limestone deposits close to the land surface, the risk of groundwater contamination might be much higher than shown on the map. Therefore, it cannot be overemphasized that the map should only be seen as a first approach in the vulnerability mapping and cannot replace detailed assessments of the pollution risk in particular areas.

Aquifer Susceptibility to Depletion in the Damascus Ghouta Plain

An integrated and diagnostic approach to the study of groundwater contamination includes the evaluation of the sensitivity of the aquifer system to possible pressures in terms of quality and quantity (J. KHOURI, 2000). In addition to the evaluation of the protective effectiveness of the soil and rock cover above the aquifer and hazard, risk and impact assessments, aquifer susceptibility to depletion plays an important role in the evaluation process. As serious as groundwater contamination problems are, under the present conditions mining of the groundwater resources poses an even bigger problem in the Damascus Ghouta.

The Barada and Auvage Authority/Ministry of Irrigation established a fairly well distributed network of groundwater level observation wells in Damascus and the Ghouta plain (Figure 11). The monitoring data from wells in the project pilot area have been evaluated for an assessment of the effects of the increasing groundwater withdrawal on the groundwater resources. Groundwater level fluctuations depend not only on the aquifer and recharge conditions but also, to a large degree, on the distance to and the withdrawal rates from pumping wells. Though rates of groundwater level declines are therefore not always representative for regional changes in the aquifer, the overall picture quite clearly shows the effects of groundwater withdrawal on the available resources.

Observed annual groundwater level declines in the Damascus Ghouta and its surroundings during the time period 1993 to 2000 reached up to more than 6 m/y. In the western and central part of the Ghouta the values ranged mostly between 1.5 and 2 m/y and usually exceeded 2 m/y in the eastern part. From a sustainable management point of view, these are very high values, especially if longer time periods are taken into consideration. The only observation well in the Turonian limestone aquifer (Well No. 174 DK), located at the northern edge of the pilot area, shows exceptionally high groundwater level declines of almost 6 m/y. Obviously, the present groundwater withdrawal rates are not sustainable. Wet years might bring relief and lead to a somewhat higher rise of water levels during the rainy season, but the long-term observations show that a complete recovery of the groundwater resources is highly unlikely.

During the three-year drought period from 1998 to 2000, the situation became even more dramatic. Though the total range of groundwater level declines is still about the same, most of the values are now between 3 and 4 m/a, especially in the Damascus area, its surroundings and in the central part of the Ghouta. Well yields are going down dramatically (often by more than 50% according to information from farmers) and the upper aquifer is falling dry in many areas. Individual farmers try to adapt to this situation by drilling deeper wells, but in many areas deep aquifers layers are less productive and the water is often more saline. On the longer run, agriculture in the Ghouta is only sustainable, if the abstraction rates are adapted to the average quantity of available resources. Those include the average annual groundwater recharge and the supply of (treated) sewage water. The latter source will probably become increasingly important in the future, especially if water import from other regions to the capital takes place.

A completely different situation can be observed in the area between Alshifoniyeh and Adra in the northern central part of the Ghouta. There, groundwater levels have been rising significantly during the recent years (up to about 8 m/a), despite the drought situation. Apparently this is caused by leakage from the sewer trunk lines for treated and untreated wastewater and/or by infiltration of excess irrigation water.

Consequences for Regional Land-use Planning

In large parts of the pilot area the information on the lithological composition of the strata above the saturated aquifer is rather poor. In some areas there are very few and far-spaced boreholes with reasonable descriptions of the lithology of the penetrated strata. The groundwater vulnerability map shows therefore a preliminary and generalized classification of the natural protective effectiveness of the soil and rock cover above the aquifer. The map can be used for general planning purposes but it cannot replace detailed assessments of the risk of groundwater contamination for particular (high-risk) activities of land use at individual sites.

As shown above, a considerable number of potentially polluting activities are located in areas where the vulnerability of the groundwater to contamination is high. At these areas, pollutants may reach the groundwater within very short periods of time posing a serious threat to the health of the population. Examples are the use of abandoned limestone quarries for waste disposal and disposal of toxic effluents from factories into riverbeds.

In general, the protective effectiveness of the soils and rock cover is relatively high in the Damascus plain. Project activities and other studies clearly indicate however, that groundwater contamination problems could seriously affect the water supply situation in the near future. Nitrate content, for example, exceeds the permissible values for drinking water in many locations.

Areas of high to very high protective effectiveness of the soil and rock cover above the aquifer can be seen as 'search areas' for waste disposal sites and the allocation of sites for industrial development or other land-use activities with pollution potential. However it has to be kept in mind that contaminated run-off from an area of low vulnerability might pollute an aquifer in an area where the protective effectiveness of the soil and rock cover is low.

4.2. Case study 2: Beka'a Plain in Lebanon.

The Beka'a plain is located between the mountainous chains of Lebanon and Anti Lebanon and it is part of the Red sea–Dead sea rift. It is the most fertile and cultivated area in Lebanon. The central part of the plain was selected as a pilot area within the ACSAD – BGR cooperation project mentioned above. The same concept and methodology for the preparation of vulnerability mapping described above, in the Ghouta has been applied in this pilot area. Soil and hydrogeological investigations were carried out to define the soil characteristics, water level variation, and soil contamination by heavy metals or nitrate. The main aquifer systems consist of the following:

- The quaternary and Neogen deposits mainly encountered in the plain and at the borders of the mountains. It is formed mostly of alluvial sediments, and clays.
- The Cenomanian-Turonian formation, out-cropping at the mountain and formed of carbonate (Figure 12).

The main aquifer of water supply is the Cenomanian -Turonian, and it is formed of karstified limestone. Several thematic maps have been prepared and are shown in Figures 13, 14, and 15. The prepared groundwater vulnerability map is shown in Figure 16. It can be seen that the most vulnerable zones are the mountainous area where most of the cities and urban centers are located. Therefore, it is obvious that some protective measurements should be taken in these areas to prevent any contamination of groundwater.

5. Conclusions:

In order to decrease the risks of continuing overexploitation of the rather limited water resources and to counter further deterioration of the groundwater quality, the following efforts should be taken:

- To prepare a 'Water Master Plan' for the entire Damascus - Ghouta region. The available resources have to be assessed and groundwater abstraction in the entire area has to be controlled.

- To continue, re-evaluate and expand the existing monitoring system for groundwater level fluctuations and water quality control (also for rural areas)
- To introduce legislation for groundwater protection (valid for the entire country)
- To delineate groundwater protection areas for water supply installations and to enforce restrictions and regulations for those areas
- To replace wellfields which cannot be protected at all by new wellfields (e.g. wells surrounded so closely by houses that even the delineation of an immediate protection zone is not possible because of lack of space)
- To seal abandoned wells properly (may act as conduits for pollutants)
- To forbid any additional high risk activities in areas of low natural protective effectiveness of the unsaturated zone and to relocate high-risk activities at more suitable locations
- To stop the disposal of toxic effluents from factories into rivers, wadi beds and irrigation channels (e.g. by on-site treatment)
- To protect the underground in high risk areas by technical means from activities/ installations which pose a high risk of pollution (e.g. proper waste storage, handling and disposal of chemicals and waste products, use of closed pipe systems for the transport of contaminated water, lining of the surface to provide water-tightness)
- To stop waste disposal in areas where the protective effectiveness of the unsaturated zone is low (worst case: abandoned limestone quarries!)
- To continue with the connection of settlements to the centralized sewer system and to plan the construction of further wastewater treatment plants
- To reduce water consumption in agriculture (e.g. installation of water–saving irrigation systems)
- To use high quality groundwater primarily for domestic purposes (in case of conflicting interests of water demand). Additional water resources for agriculture should mainly come from treated sewage water.
- To educate farmers not to apply overdoses of fertilizers, to use pesticides sparingly and to follow the proper procedures in handling these substances.
- To regulate groundwater abstraction from private wells.

Groundwater vulnerability mapping should be seen as a powerful tool to introduce aspects of groundwater protection in land-use planning. The mapping results, however, represents preliminary and generalized classifications of the protective effectiveness of the soil and rock cover above the aquifer. Due to uncertainties in the assessment process more detailed investigations will always be necessary for the determination of the suitability of a selected site for particular purposes.

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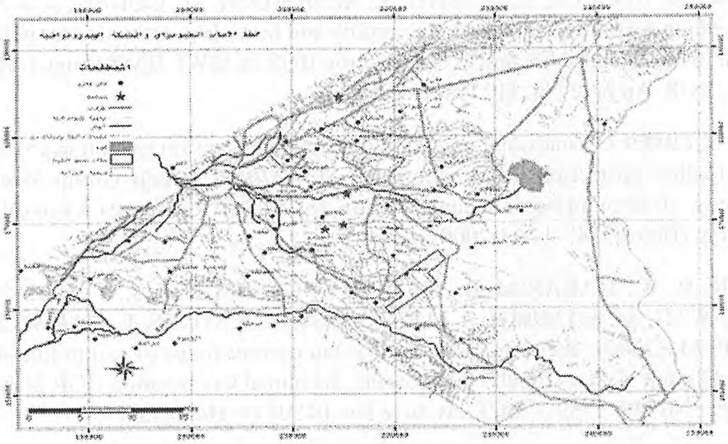


Fig. (1) Location of Damascus Ghouta Plain and hydrographic network.

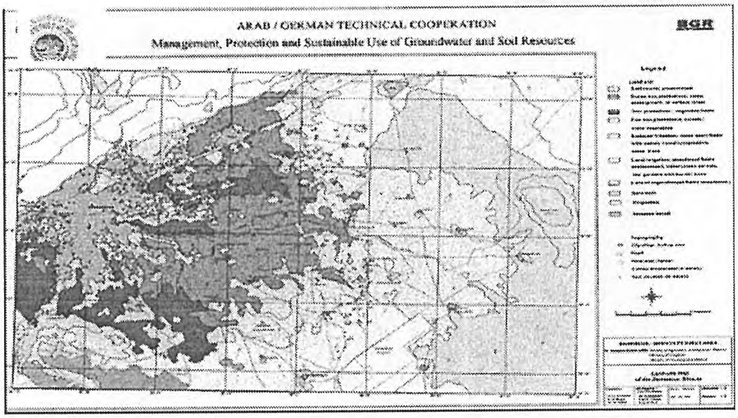


Fig. (2) The Landuse map of the GHOUTA area.

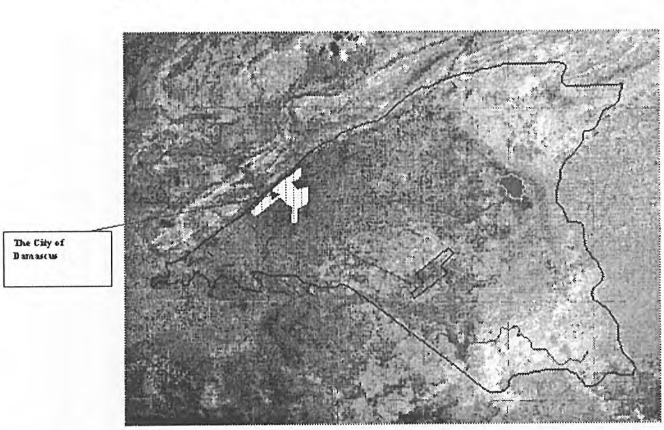


Fig. (3) Satellite image showing the vegetative cover in Ghouta Plain (2002)

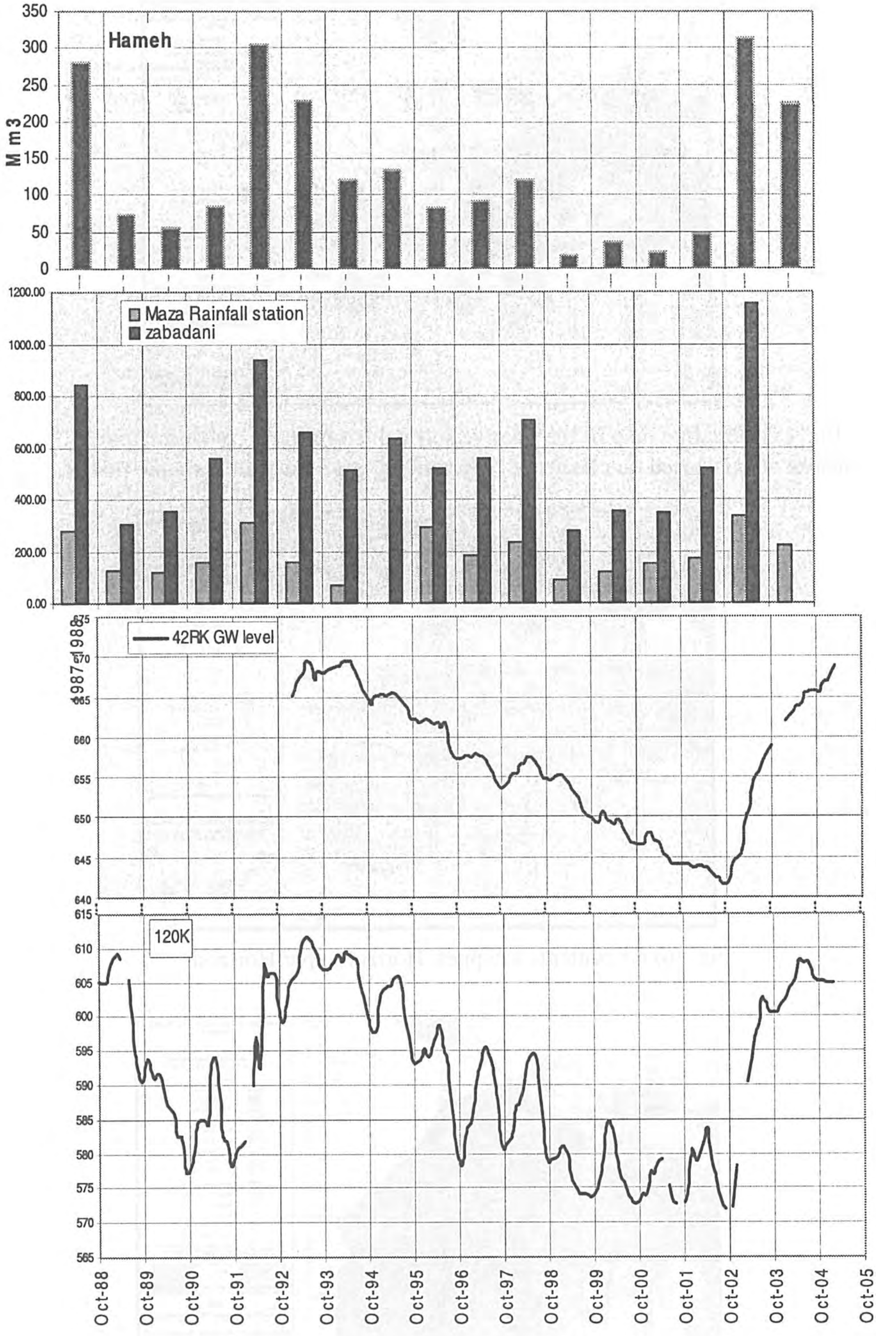


Fig. (4) Variation of groundwater level in relation to rainfall distribution

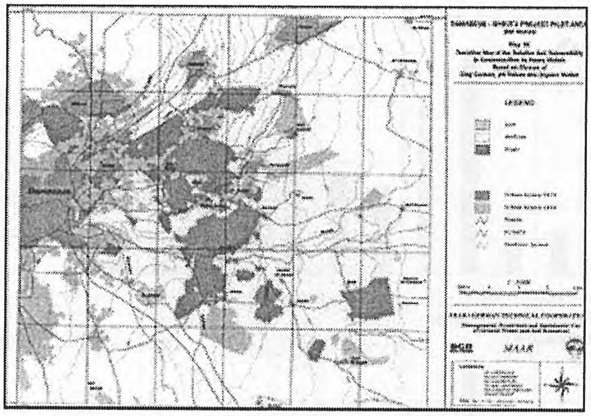


Fig. (5) Tentative map of the relative soil vulnerability to contamination by heavy metals based on classes of clay content, pH values and organic matter.

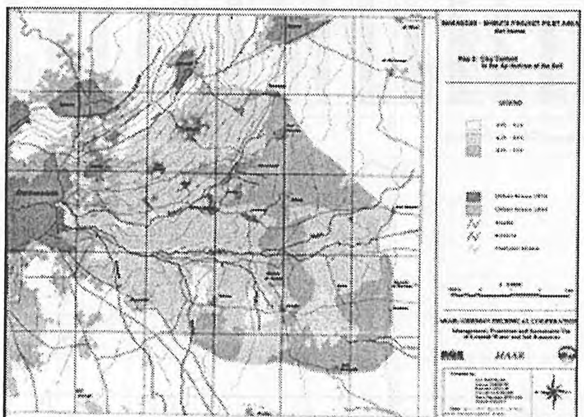


Fig. (6) Cr contents in upper Horizonupper Horizon.

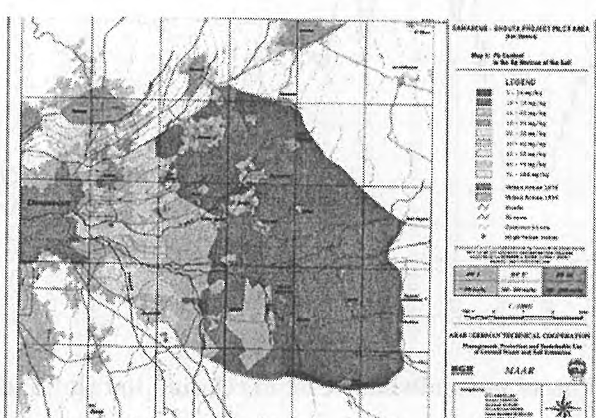


Fig. (7) PB contents in upper horizon.

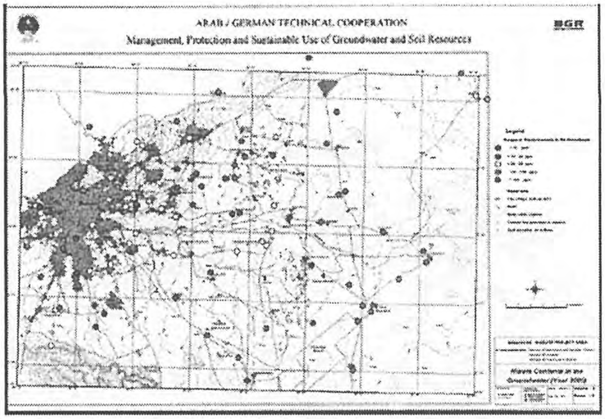
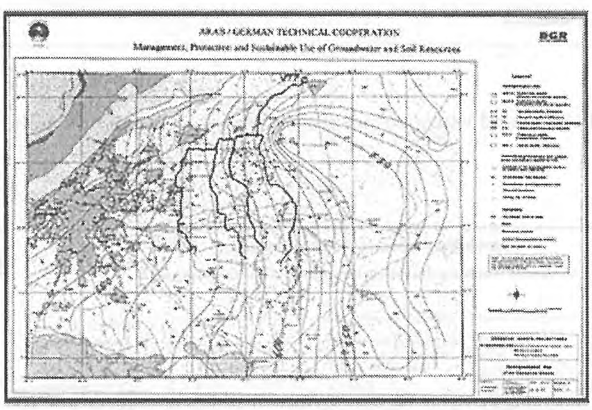


Fig. (8) Concentration of Nitrate in the groundwater.



9) Groundwater contour map in Ghouta plain

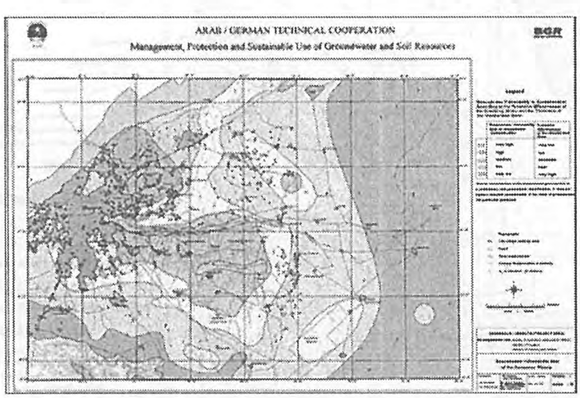


Fig. (10) Groundwater vulnerability map of Ghouta plain

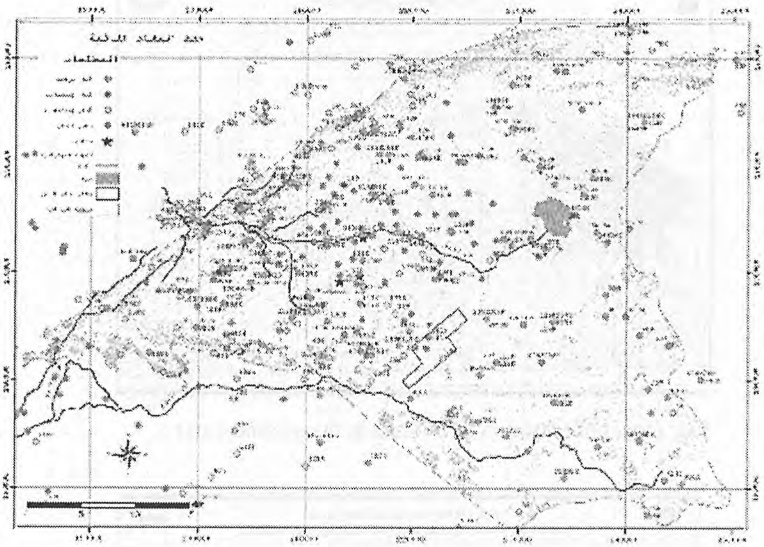


Fig. (11) Ground water observation network in Damascus (Ghouta).

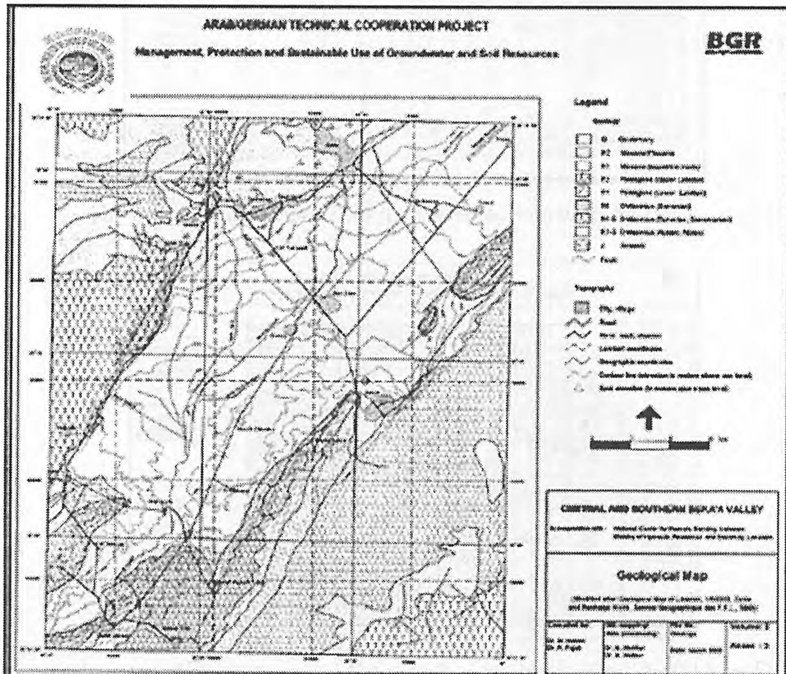


Fig. (12) Geological map of Bekaa plain (Lebanon)

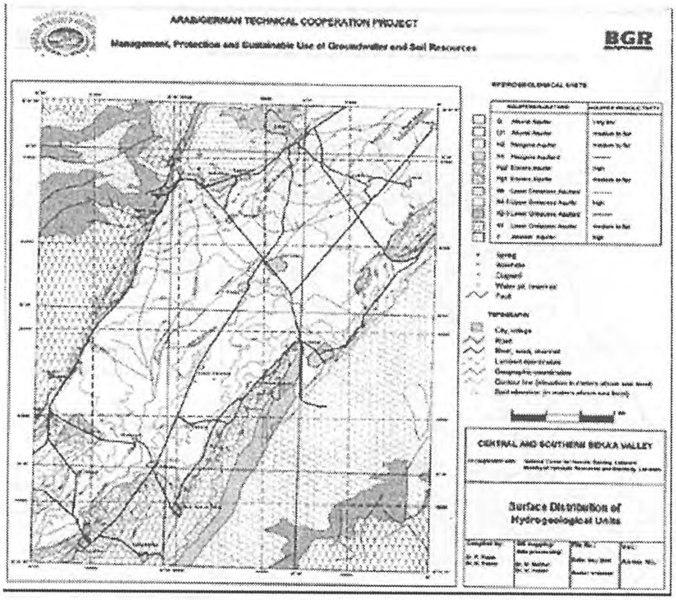


Fig. (13) main aquifer units in Bekaa plain (Lebanon

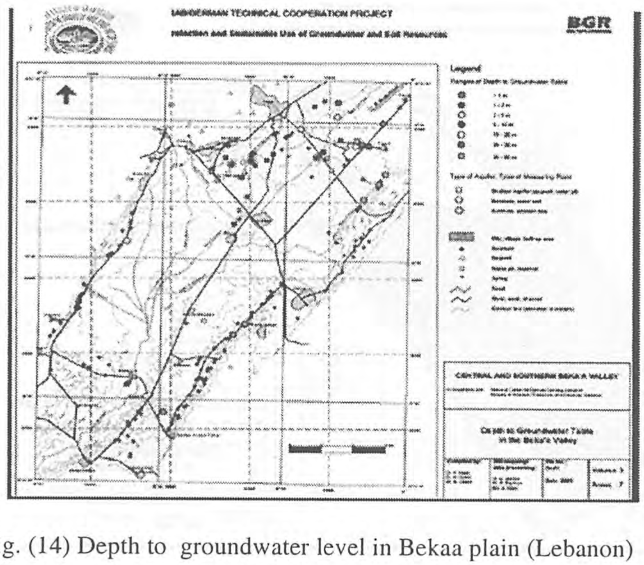


Fig. (14) Depth to groundwater level in Bekaa plain (Lebanon)

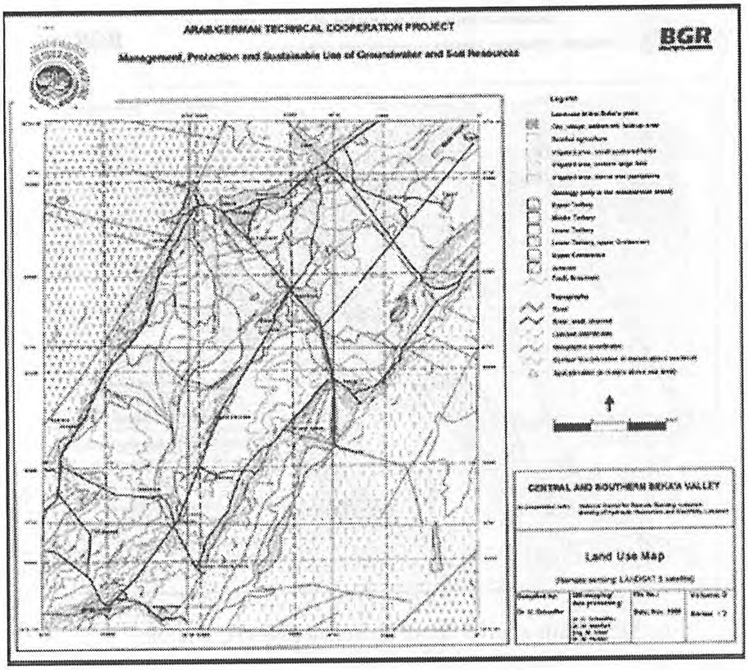


Fig. (15) land use map in Bekaa plain (Lebanon)

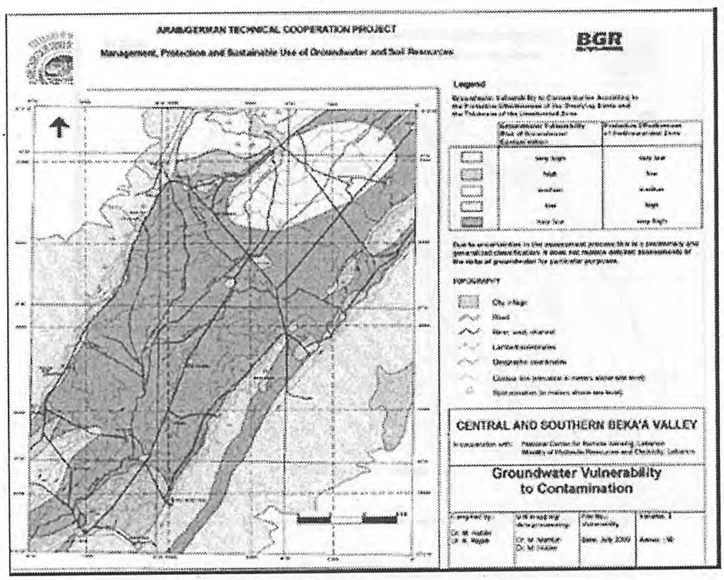


Fig. (16) The Groundwater vulnerability map in Bekaa plain (Lebanon)

Application of mathematical models in Developing and managing coastal groundwater: Physical approaches, numerical developments, and applications

A. Larabi and A. Aharmouch

APPLICATION OF MATHEMATICAL MODELS IN DEVELOPING AND MANAGING COASTAL GROUNDWATER: PHYSICAL APPROACHES, NUMERICAL DEVELOPMENTS AND APPLICATIONS

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ABSTRACT

The management of groundwater resources involves the allocation of groundwater supplies and water quality to competing water demands and uses. The resource allocation problem is characterized by conflicting objectives and complex hydrologic and environmental constraints, especially in coastal aquifers. The development of mathematical simulation models provides groundwater planners with quantitative techniques for analyzing alternatives groundwater resources management. Coastal aquifers involve varying conditions in time and space, owing to the occurrence of seawater intrusion, leading to upconing due to intensive pumping near the coast. An overview of modelling seawater intrusion in coastal aquifers is presented, including the physical approaches that assume the occurrence of a sharp interface or solute transport mixing zone. Some analytical solutions have been also outlined as to serve benchmark problems for testing developed numerical algorithms for sharp and solute transport interfaces. Based on the two physical approaches, numerical models have been developed and using conventional finite differences, finite elements and boundary integral techniques. Results of some field applications are presented to show the utility and the capability of these tools of predicting accurate information with regard to seawater intrusion, its extent, interface upcoming, critical pumping rates and other information on management issues. These information are required to assist managers, planners and decision makers for an integrated water resources management as demonstrated by the regional models developed for some coastal aquifers.

Key words : Coastal aquifers, Seawater intrusion, Modeling, Groundwater management.

1. Introduction

Management of a groundwater system means making such decisions as to the total quantity of water to be withdrawn annually, the locations of wells for pumping and for artificial recharge and their rates and control conditions at aquifer boundaries in addition to decisions related to groundwater quality. In order to assist the planner, or the decision maker, to compare alternative models of action and to ensure that the constraints are not violated, a tool is needed that will provide information about the response of the system to various alternatives. Good management requires the ability to predict the aquifer's response to planned operations, that may take the form of changes in the water levels, changes in water quality, or land subsidence (Bear and Veruijt, 1987).

The necessary information about the response of the system can be provided by a model that describes the behavior of the considered system in response to excitation. During the past 40 years, the field of aquifer management modeling has developed as a distinct discipline. It has provided a framework which replaces trial and error simulations. Modern aquifer management models combine simulation tools with optimization techniques. This combination of the optimization and aquifer simulation provides a framework that forces the engineer or hydrogeologist to formulate carefully the groundwater management problem. The problem must contain a series of constraints on heads, drawdowns, pumping rates, hydraulic gradients, groundwater velocities, and solute concentrations. In addition, an objective, usually involving costs, cost surrogates, or risk, must be seated.

This is the case of aquifers in islands and coastal areas which are prone to seawater intrusion. Because seawater is denser than freshwater, it will invade aquifers which are hydraulically connected to the sea. Under natural conditions, freshwater recharge forms a lens that floats on top of a base of seawater. This equilibrium condition can be disturbed by changes in recharge and/or induced conditions of pumping and artificial recharge. Seawater intrusion must be addressed in managing groundwater resources in islands and coastal areas. The freshwater lens is very susceptible to contamination, and once contaminated, it can be very difficult to restore to pristine conditions. To plan counter measures, it is necessary to predict the behaviour of groundwater under various conditions, such as to determine the extent to which ingress of seawater occurs. As seawater intrusion progresses, existing pumping wells, especially close to the coast, become saline and have to be abandoned, thus reducing the value of the aquifer as source of freshwater. Also, the area above the intruding seawater wedge is lost as source of water.

The contact between freshwater and seawater in islands and coastal aquifers, requires special techniques of management, because of varying conditions in time and space, such as pumping near the coast. In response to pumping from a well in the fresh-water zone, the fresh-saltwater interface moves vertically toward the well causing the upconing phenomenon. The problem of saltwater intrusion can be analysed by two methods. The first method considers both fluids miscible and takes into account the existence of transition zone (Voss and Souza, 1984). The second method is based on an abrupt interface approximation (Bear and Verruijt, 1987) where it is assumed that (i) the freshwater and saltwater do not mix and (ii) are separated by a sharp interface. This method is considered as appropriate approximation in the case where the extent of the transition zone is relatively small compared to the aquifer thickness. The first attempts to solve the saltwater intrusion were based on the assumption of the existence of a sharp interface between freshwater and saltwater (Strack, 1976; Collins and Gelhar, 1971).

In this paper, we discuss different aspects of seawater intrusion in coastal aquifers, since the famous works of Badon-Ghyben (1888). Some analytical solutions available for both sharp interface and transition zone approaches are also reviewed, as they serve as benchmark examples for testing developed numerical models and codes. Also, some 3-D numerical models are presented which enables the prediction of the fresh-saltwater interface displacement in response to varying conditions in time and space. Applications of these codes to some field cases are also given assuming both approaches of the abrupt interface and the mixing zone. The freshwater-saltwater interface is determined, including its location, shape and extent. Examples of the regional models, presented in this work, are based on the Galerkin finite element approach (Larabi and De Smedt, 1994) and the finite difference technique (Mcdonalds and Harbaugh, 1988). These models are capable to simulate groundwater flow, solute transport and the transient interface displacement due to groundwater exploitation, especially under upconing conditions due intensive pumping. Although simulation models provide the resource planner with important tools for managing the groundwater system, the predictive models do not identify the optimal groundwater development, design, or operational policies for an aquifer system. Hence, they should be combined to groundwater optimization models to identify the optimal groundwater planning or design alternatives in the context of the system's objectives and constraints (Willis and Yeh, 1987).

2. Approaches to modeling seawater intrusion

2.1 Occurrence of seawater intrusion

The occurrence of seawater intrusion in coastal aquifers can be visualised with a simplified conceptual model (Figure 1). The essential elements are freshwater recharge from inland sources, seawater intrusion from the ocean and an interface or transition zone between the two types of water. The transition zone is a zone of mixing between the freshwater and the saltwater (Figure 2). Under equilibrium conditions, the interface will remain fixed, and freshwater will discharge along the seepage face. In coastal aquifers, recharge is predominantly due to lateral inflow, whereas in island aquifers, it is due to vertical recharge. These conceptual models are analysed in different ways. Coastal aquifers are usually modelled in the vertical plane. Island systems are also analysed in the vertical plane when the thickness of the freshwater lens is a significant fraction of the horizontal width of the lens, a situation common in atoll islands. When the lens thickness is small compared with its horizontal extent, the system can often be treated in the horizontal plane.

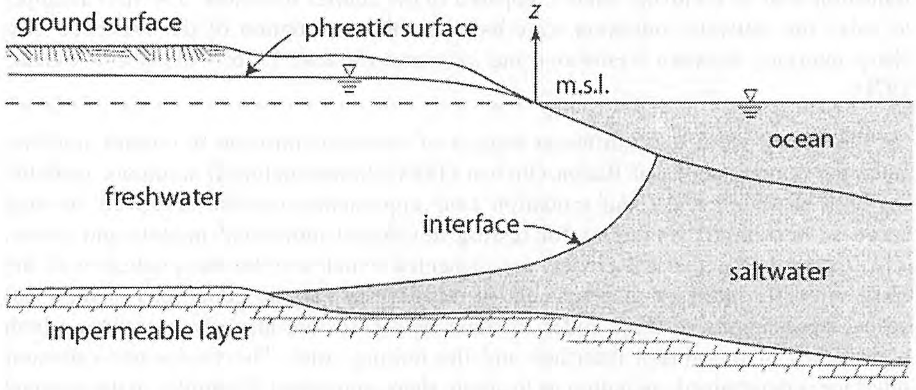

Figure 1: Schematic sketch of saltwater intrusion, sharp interface model.

2.2 Approaches for sharp interface and miscible flow models

The first question in developing a simulation model is whether it is appropriate to deal with the problem as miscible or immiscible flow. If the transition zone is thin relatively to the thickness of the freshwater lens and it is immobile, then it is appropriate to assume that the freshwater and saltwater don't mix (immiscible), and the transition zone is considered to be a

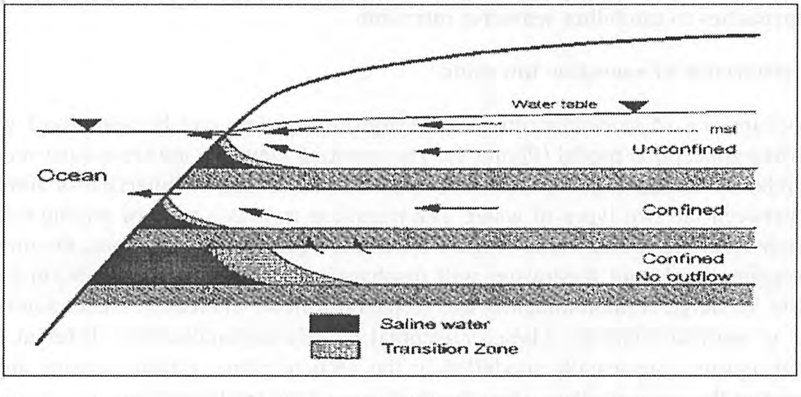

Figure 2: Salt/fresh water transition zone in multi-layered aquifer.

sharp interface. There are several methods for dealing with seawater intrusion as two-phase, immiscible problem. These methods are generally known as interface methods. Under very dynamic conditions, or in case where the freshwater lens is relatively thin compared with the transition zone, it may be necessary to adopt miscible flow models. Reilly and Goodman (1985) presented a historical perspective of quantitative analysis of the saltwater freshwater relationship in groundwater systems. Custodio (1992) reported that both approaches produce good results if applied to the right circumstance. Pinder and Stothoff (1988) pointed out that the sharp interface assumption is appropriate for steady state conditions. Additionally, if conditions of variable recharge and/or significant pumping exist, the interface will move in response to the non equilibrium conditions. For this problem, the hydraulic head and fluid velocity in both the fresh and salt portions of the aquifer must be considered. Since these quantities are unknown, the problem becomes one of coupling differential equations for motion of the freshwater and saltwater, and solving for the unknown position of the interface between them.

In fact when the sharp interface approximation is inappropriate owing to the large thickness of the transition zone relative to the freshwater lens, it is advisable to treat the freshwater and saltwater as miscible. There are two elements to the problem: 1) a single fluid phase with variable density; and 2) a solute representing the total dissolved solids in seawater, which affects the fluid density. As a result, there are four unknown dependent variables: fluid specific discharge, fluid pressure, salt concentration, and fluid density, requiring the solution of four equations (Frind and Mangata, 1985). Often the most disruptive influence is the effect of pumping activities. Withdrawal of water from the freshwater lens via pumping wells creates saltwater upconning, which is the migration of the fresh-salt interface towards a well in response to pumping withdrawals. However, Bear (1979) has given some examples of real aquifers in which experimental measurements have shown the salt concentration to vary sharply at a determined location, clearly establishing a region of low salt concentration (freshwater) and a region of high salt concentration (saltwater).

3. Analytical solutions and benchmarking

3.1 Key role of analytical solutions

In fact, analytical solutions can not solve 'real-world' problems, due to their simplified physical assumptions and geometry. But they play an important role to serve a number of important purposes such as instructional tools to present fundamental insights to clearly understand the mechanical trend of the groundwater flow in coastal aquifers, while numerical solutions are often difficult to provide it.

In addition and despite their simplifying assumptions, analytical solutions can also be used as a tool for first-cut engineering analysis in a feasibility study. More sophisticated models normally require hydrological and hydrogeological information that is either not available or not known to the required solution at the time of initial investigation. Hence, without the support of reliable input data, these sophisticated models cannot provide more accurate results. That is why before a large scale site study, or a comprehensive numerical modelling, it is often interesting to perform some preliminary calculations based on basic information and simplifying assumptions.

However, still the most important contribution of the analytical solutions is to serve as benchmark problems for testing numerical algorithms. Numerical models, especially newly developed ones based on numerical techniques such as FE, FD, BE or mixed techniques, need to be verified and validated against programming and other errors before distribution for use and/or for real world applications.

3.2 Interface models

An exact mathematical statement of the saltwater intrusion problem, assuming that an abrupt interface separates fresh water and saltwater, was presented by Bear (1979). However, in order to simplify the problem, the Ghyben-Herzberg relationship can be introduced. The vertical position of the saltwater interface measured from the sea level, zi, is given by

$$z_i = \frac{\rho_f}{\rho_s - \rho_f} z_w = \frac{z_w}{\delta} \qquad (1)$$

where $\delta = (\rho s - \rho f)/\rho f$ and zw is the position of the water table measured above sea level. Assuming a sea water density ρs of 1025 kg/m3, and a fresh water density ρf of 1000 kg/m3, this relationship predicts that there will be approximately 40 times as much fresh water in the lens beneath sea level as there is fresh water above sea level.

Bear and Dagan (1964) investigated the validity of the Ghyben-Herzberg relationship. The hodograph method was used to derive an exact solution and it was shown that close to the coast the depth of the interface is greater than that predicted by the Ghyben-Herzberg relationship.

Analytical solutions for the interface problem based on the Dupuit assumption can be found in the works of Strack (1987), Van Dam (1983), and Bear (1979). These analytical models give reasonable results if the aquifer is shallow, but lack accuracy in the region of significant vertical flow components. This assumption is also incapable to handle anisotropy and nonhomogeneity of the aquifer. Only a few analytical solutions are available for layered aquifers (Mualem and Bear, 1974; Collins and Gelhar, 1971).

The simplest stationary interface solution based on this assumption was proposed by Glover (1959) for confined flow, later extended by Van der Veer (1977) to include phreatic flow. In the Glover solution the aquifer is assumed to be confined, with a bounding layer positioned at sea level. The origin of the coordinate system is chosen at the contact point of the sea and the continent. The saltwater interface can be considered as a streamline and, its position can be determined as a function of the distance from the shoreline, (Glover, 1959)

$$z_i = \sqrt{\left(\frac{Q}{\delta K}\right)^2 + \frac{2Q}{\delta K} x} \qquad (2)$$

where Q is the constant total freshwater flow per unit length of shoreline [L2T-1]. The width of the region through which freshwater discharges to the ocean is given by

$$x_0 = -\frac{Q}{2\delta K} \qquad (3)$$

If the fresh water flow Q can be estimated or measured, then equation (2) provides a simple method to calculate the depth to saltwater in the coastal zone. Alternatively x0 can be estimated.

Detournay and Strack (1988) derived an approximate analytical solution technique to solve groundwater flow which involves the determination of a phreatic surface, an interface separating flowing fresh water from saltwater at rest, and seepage and straight outflow faces where fresh water discharges into the sea, by application of conformal mapping techniques using the hodograph method. Results are presented in a table, where the coordinates of the phreatic surface and the interface are calculated for the flow case in which the coast and the sea bottom slopes have angles of respectively 30o and 15o with the x-axis.

Van der Veer (1977) has proposed an analytical solution for the steady interface flow in coastal aquifer flow systems involving recharge on the top phreatic surface.

Strack (1976), developed an analytical solution for regional interface problems in coastal aquifers based on single-valued potentials and the Dupuit assumption and the Ghyben-Herzberg formula, in the context of steady state. The critical pumping rate has been also computed in the case of a fully penetrating well. Motz (1992) proposed an analytical solution for calculating the critical pumped flow rate in an artesian aquifer for a critical interface rise supposed to be 0.3(b – l), where b denotes the aquifer thickness and l the distance from top of aquifer to bottom of well screen (figure 2). Bower *et al.*(1999) modified the critical interface rise based on an analytical solution, which allows the critical pumping rate to be increased.

Solutions for the miscible fluid model with dispersion have also been obtained by a number of investigators. Henry (1964) used a Fourrier-Galerkin method, but was restricted in the choice of the parameters by convergence requirements of the method. This was the first solution for predicting the steady state salt distribution in a cross section of a confined coastal aquifer.

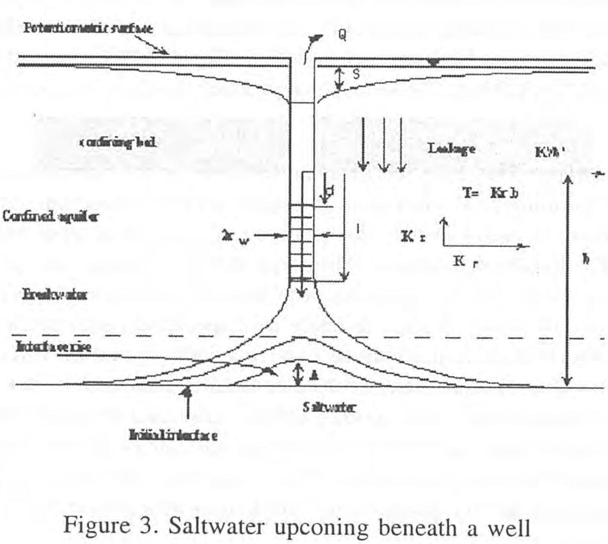

Figure 3. Saltwater upconing beneath a well

3.3. Benchmark models

For the sharp interface benchmarking, a 3-D sand model (Sugio, 1992) has been designed to study saltwater intrusion into freshwater in a sand box. This laboratory model consists of a 3-D sand box, 163.8cm long and 47.5cm high, while the width of the model has two values : 63.2cm from the downstream end until the length 82.3cm, and 30cm in the remaining part. Salt was added to the fresh water and thoroughly mixed up to the density of 1030kg/m^3 to model sea water, and then was colored by dye in order to observe the position of the interface separating fresh water and saltwater. Sand with 0.76mm mean diameter was used for which the hydraulic conductivity was obtained from measurements (Sugio, 1992) as 1.293cm/s. The upstream and downstream water levels are respectively h_l = 44.15cm and z_s = 40.67cm. Fresh water flows through the sand model for about three hours to achieve steady state conditions. The behaviour of the fresh water-saltwater interface was measured on the front, side and bottom sections of the box model. This sand model is used to test the numerical model capability to accurately simulate 3-D groundwater flow problems with a fresh water-saltwater interface as it was demonstrated by the GEO_SWIM code (Larabi, 1994).

Three well known benchmark problems in the literature have been selected to be presented for validation purposes of the developed numerical models based on variable density dependent flow and solute transport in coastal aquifers:

The Henry's problem: This test (Henry, 1964) deals with the advance of a salt water front in a uniform isotropic aquifer limited at the top and the bottom by impermeable boundaries recharged at one side by a constant freshwater influx, and faced the sea on the other side with hydrostatic pressure distribution. For the mass fraction conditions, the influx side is at c= 0, the top part of the sea side is treated in a manner to permit convective mass transport out of the system (outflow face) and the remained part of the seaside is at c=1. Many numerical codes have been evaluated and tested with the Henry's solution. Segol (1993) showed, however that the Henry's solution was not exact because Henry (1964) eliminated, for computational reasons, mathematical terms from the solution that he thought to be insignificant. When Segol (1993) recalculated Henry's solution with the additional terms, the improved answer was slightly different from the original solution. With the new solution, Segol (1993) showed that numerical codes, such as SUTRA (Voss, 1984), could reproduce the correct answer for the Henry problem.

The Elder's problem: This case serves as an example of free convection phenomenon originally used for numerical analysis of thermally driven convection. After adaptation, this test benchmark is used to verify the accuracy of a model in representing fluid flow purely driven by density differences. The large density contrast (1.2 to 1) constitutes a strong test for coupled flow problems. The domain is represented by a rectangular box with a source of solute at the top taken as a specified concentration boundary (c = 1), whereas the bottom is maintained at zero concentration (c = 0). For the flow conditions, zero value of equivalent freshwater head is attributed to the upper corners. Several authors studied this case, among others, Voss and Souza (1987), Oldenburg and Pruess (1995), Kolditz *et al.*(1998) Aharmouch and Larabi (2004). This problem was originally designed for heat flow (Elder, 1967), but Voss and Souza (1987) recast the problem as a variable density groundwater problem in which fluid density is a function of salt concentration.

The salt dome (HYDROCOIN level 1, case 5): The purpose of the Hydrologic Code Intercomparison (HYDROCOIN) project was to evaluate the accuracy of selected groundwater modelling codes. One of the problems used for testing is the HYDROCOIN problem. This test is used to model variable density groundwater over a salt dome. The boundary conditions are: the hydraulic head varies linearly on the top of the aquifer whereas the other sides are impervious. The mass fraction ($c = 0$) on the top at the inflow part while the central base of the aquifer is at $c = 1$. For this problem, Herbert *et al.*(1988) presented a steady state solution based on the parameter stepping technique.

More literature on these benchmark examples can be found in several papers such as those of Voss and Souza (1987), Oldenburg and Pruess (1995) and Kolditz *et al.*(1998), among other authors.

4. Numerical models

4.1 Numerical methods for groundwater management

Numerical modeling has emerged over the past 40 years as one of the primary tools that hydrologists use to understand groundwater flow and saltwater movement in coastal aquifers. Numerical models are mathematical representations (or approximations) of groundwater systems in which the important physical processes that occur in the systems are represented by mathematical equations. The governing equations are solved by mathematical numerical techniques (such as finite-difference, finite-element, boundary finite element, or finite volume methods) that are implemented in computer codes. The primary benefit of numerical modeling is that it provides a means to represent, in a simplified way, the key features of what are often complex systems in a form that allows for analysis of past, present, and future groundwater flow and saltwater movement in coastal aquifers. Such analysis is often impractical, or impossible, to perform by field studies alone. Numerical models have been developed to simulate groundwater flow solely or groundwater flow coupled to solute transport (the movement of chemical species through an aquifer). For a number of reasons, numerical models that simulate groundwater flow and solute transport are more difficult to develop and to solve than those that simulate groundwater flow alone. Coastal aquifers are particularly difficult to simulate numerically because the density of the water and the concentrations of chemical species dissolved in the water can vary substantially throughout the modeled area. Numerical models based on the sharp interface approximation assumption are reported in Mercer et al. (1980), Polo and Ramis (1983), Essaid (1990), Larabi and De Smedt (1994a, 1994b, 1997). Huyakom et al. (1987), Galeati et al. (1992), Das and Datta (1995, 1998), Putti and Paniconi (1995), Langevin and Guo (2002), and Aharmouch and Larabi (2004) present some of the recent developments in modeling of seawater intrusion in coastal aquifers for density dependent miscible flow and transport.

Two and Three-dimensional, dynamic numerical models handle more complex situations under realistic representation of the mechanisms involved and account for variability in physical situations. Three-dimensional models are more realistic and yields better insight. They are particularly effective in handling irregularities in coastal aquifer geometry, water use; heterogeneity in aquifer formations; temporal variations in boundary conditions; and spatial variations in salt concentrations. Therefore, these models can provide greater detail and accurate results. The only drawback is related to the intensive computational cost (memory and CPU) and the amount of data needed to feed up these models.

4.2 Governing equations for groundwater flow and solute transport models

Analysis of saltwater intrusion, assuming that mixing occurs at the transition zone between seawater and freshwater, because of hydrodynamic dispersion, requires the solution of two partial differential equations representing the mass conservation principle for variable-density fluid (flow equation) and for the dissolved solute (transport equation). The mathematical model of density-dependent flow and transport in groundwater is expressed here in terms of an equivalent freshwater total head (for more details see Langevin, 2003): The variable density groundwater flow is described by the following partial differential equation:

$$\nabla \cdot \rho K_f + \left(\nabla h_f + \frac{(\rho - \rho_f)}{\rho_f} \nabla z \right) = \rho S_f \frac{\partial h_f}{\partial t} + n \frac{\partial \rho}{\partial C} \frac{\partial C}{\partial t} - \overline{\rho q} \quad (4)$$

Where:

x,y, and z are coordinate directions; z is aligned with gravity (L).

ρ is fluid density (ML-3).
K_f is the equivalent fresh water hydraulic conductivity (LT-1).
h_f is the equivalent fresh water head (L).
ρ_f is the density of fresh water (ML-3).
S_f is equivalent fresh water storage coefficient (L-1).
t is time (T).
n is porosity (L0).
C is the concentration of the dissolved constituent that affects fluid density (ML-3).
$\overline{\rho}$ is the fluid density of a source or a sink (ML-3).
$\overline{q}$ is the flow rate of the source or sink (T-1).

To solve the variable density ground water flow equation, the solute-transport equation also must be solved because fluid density is a function of solute concentration, and concentration may change in response to the groundwater flow field. For dissolved constituents that are conservative, such as those found in seawater, the solute transport equation is:

$$\frac{\partial C}{\partial t} = \nabla \cdot (D \nabla C) - \nabla \cdot (\nu C) - \frac{q_s}{n} C_s \quad (5)$$

Where:

D is the dispersion coefficient (L2T-1).
ν is the groundwater flow velocity (LT-1).
q_s is the flux of a source or sink (T-1).
C_s is the concentration of the source or sinks (ML-3).

4.3 Recent Numerical Codes

Currently, several solute transport models suitable for the simulation of seawater intrusion and up-conning of saline water beneath pumping sites are available. These include SUTRA (Voss, 1984), which is a two-dimensional, vertical cross-sectional model; SEAWAT (Guo and Bennett, 1998), CODESA3D (Gambolati et. al., 1999), GEO_SWIM (Aharmouch and Larabi, 2004) and FEFLOW (Diersch, 2004) are examples of three-dimensional models. These models provide solution of two simultaneous, non-linear, partial differential equations that describe the conservation of "mass of fluid" and "conservation of mass of solute" in porous media; as described above.

<u>SUTRA</u>

SUTRA (which is named from the acronym Saturated Unsaturated TRAnsport) was published by the United States Geological Survey (Voss, 1984). The model is two-dimensional and can be applied either aerially or in a cross-section to make a profile model. The equations are solved by a combination of finite element and integrated finite difference methods. Although SUTRA is a two-dimensional model, a three-dimensional element is provided since the thickness of the two-dimensional region may vary over the solution domain. The coordinate system may be either Cartesian or radial which makes it possible to simulate phenomena such as saline up-coning beneath a pumped well. SUTRA permits sources, sinks and boundary conditions of fluid and salinity to vary both spatially and with time. The dispersion processes available within SUTRA are particularly comprehensive. They include diffusion and a velocity-dependent dispersion process for anisotropic media. This means that it is possible to model the variation of dispersivity when the flow direction is not along the principal axis of aquifer transmissivity.

<u>SEAWAT</u>

The original SEAWAT code was written by Guo and Bennett (1998) to simulate ground water flow and salt water intrusion in coastal environments. SEAWAT uses a modified version of MODFLOW (McDonald and Harbaugh 1988) to solve the variable density, ground water flow equation and MT3D (Zheng, 1990) to solve the solute-transport equation. To minimize complexity and runtimes, the SEAWAT code uses a one-step lag between solutions of flow and transport. This means that MT3D runs for a time step, and then MODFLOW runs for the same time step using the last concentrations from MT3D to calculate the density terms in the flow equation. For the next time step, velocities from the current MODFLOW solution are used by MT3D to solve the transport equation. For most simulations, the one-step lag does not introduce significant error, and the error can be reduced or evaluated by decreasing the length of the time step.

CODESA3D

CODESA-3D (COupled variable DEnsity and SAturation 3-Dimensional model) can solve the density-dependent miscible flow and transport equations and predict solute migration. It is a three-dimensional finite element simulator for flow coupled to solute transport in variably saturated porous media on unstructured domains (Gambolati et. al., 1999; Lecca, 2000). The numerical model is a standard finite element Galerkin scheme, with tetrahedral elements and linear basis functions, and weighted finite differences are used for the discretization of the time derivatives. Model parameters that are spatially dependent are considered constant within each tetrahedral element. Parameters that depend on pressure head and/or concentration are evaluated using values averaged over each element and are also element-wise constant. The CODESA-3D code is born from the integration and extension of parent codes developed, during the last ten years, by the Department of Applied Mathematics of the University of Padova in collaboration with the Environment Group of CRS4 (Center for Advanced Studies, Research and Development).

GEO_SWIM

GEO_SWIM (GEOprofessional SaltWater Intrusion Model) is a 3-dimensional finite element model for variable density flow and solute transport in variably saturated porous media. The Galerkin technique is used for the spatial discretization, using hexahedral elements, with a finite difference for time discretization. The mathematical model is made of a set of nonlinear coupled PDE's of flow and solute transport to be solved for hydraulic head and mass fraction of the solute component. The flow equation simulates the water movement in the porous medium whereas the transport equation calculates the displacement of the dissolved salt. The accuracy of the model has been checked via the most commonly used benchmark tests (Aharmouch and Larabi, 2004 and 2005), either for seawater intrusion (Henry's problem) or brine transport (Elder's problem and Hydrocoin test). Application of the model had been realized in the case of seawater intrusion in some coastal aquifers situated in Morocco (Aharmouch and Larabi, 2004). A version of the code also exists for handling the sharp interface case (Larabi and De Smedt, 1997).

FEFLOW

FEFLOW (Diersch, 2004) is a finite element groundwater modelling commercial code developed by WASY AG (Germany). The code solves groundwater flow, solute transport, density dependent solute transport, coupled heat and flow, saturated and unsaturated flow. Different types of licenses are available at different prices depending on the type of problems that the user needs to solve. The cheapest version includes only 2D groundwater flow, while the most expensive includes 3D flow, transport, and heat processes. The code includes different types of elements that can be combined. This allows for example to model 2D planar structures such as a fault plane within a porous matrix or linear elements such as a drain or a stream in which the flow equation may be different than within the porous matrix. The code solves both steady state and transient equations.

5. Applications

5-1. The Oued-Laou coastal aquifer (GEO_SWIM code)

The Oued-Laou coastal aquifer is located 48 km to the southeast of Tétouan city, in the northwestern part of Morocco, on the Mediterranean coast. This 18 km² alluvial aquifer is the region's major groundwater source for potable water supply and irrigation. The aquifer is widely opened on the sea and it is composed of plio-quaternary material (El Amrani et al., 2004).

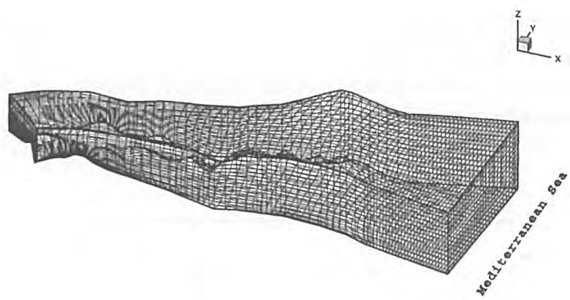

Figure 4: 3-D structured mesh of Oued-Laou aquifer

The conceptual model used in this study is a one-layer aquifer system of variable thickness. Figure 4 shows the 3-D structured mesh of Oued-Laou aquifer. The mesh is adjusted to fit the aquifer geometry and the well locations. The GEO_SWIM code (abrupt interface version) was applied to the aquifer system to describe groundwater flow to determine the seawater intrusion interface behavior.

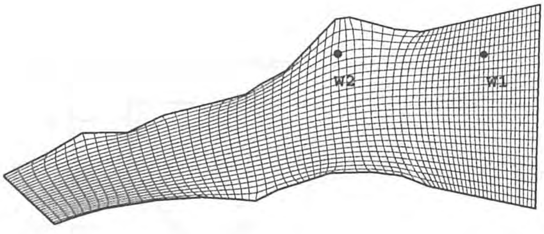

Figure 5: Plan view of the aquifer with pumping well locations.

Two wells are located as shown in Figure 9, one close to the coastline with pumping rate of 661.3 m^3/day for potable water supply, and one inland with pumping rate 148.4 m^3/day for irrigation. For management purposes, two scenarios are investigated for the extent of the interface location. The first scenario considers the same set of data as described above, except that the rainfall rate is reduced to half ($q_0 = 0.0006$ m/day). In the second scenario, in addition to the reduction of rainfall, the pumping rates are amplified to 2,800 m^3/day for the water supply well and 600 m^3/day for the irrigation well. The simulated results of these two scenarios are compared to those published by Larabi and De Smedt (1997). Figures 6 and 7 show the interface position in cross section and plane views. The numerical results obtained by the two numerical models are in good agreement. For scenario 1, the pumped rates don't represent a threat for the freshwater inland, instead the reduced replenishment. For the second scenario however, the supposed pumping rates constitute the critical exploitation feature. Indeed, upconing is developed beneath the pumping well w1 near the coast, however, the interface don't reach the well bottom. On the other hand, freshwater can be safely pumped from well W2.

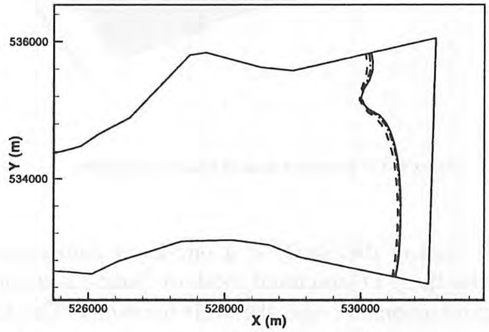

Figure 6. Position of the interface toe (scenario 2). Present model (dashed and solid lines for sets 1 and 2 respectively) and Larabi and De Smedt (1997) model (dash-dot line).

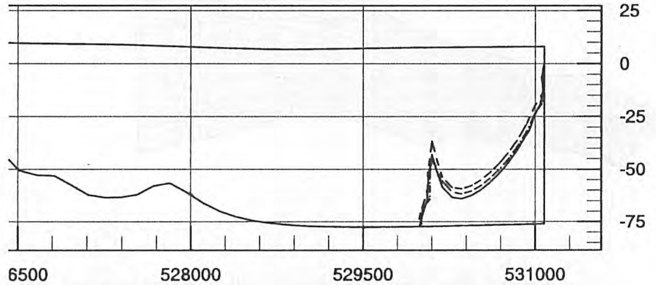

Figure 7: Vertical cross-section through pumping well W1 showing the interface position (scenario 2). Present model (dashed and solid lines for sets 1 and 2 respectively) and Larabi and De Smedt (1997) model (dash-dot line).

Transient simulations have been also performed to analyse the solute transport interface motion. The initial condition for our simulations is static saturated domain without salt. The two wells implanted near the coastline are also considered. Figures 8 and 9 show the concentration distribution respectively on a vertical section close to the pumping wells and on the bottom of the aquifer, at time simulation t = 8 years.

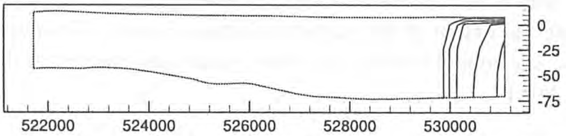

Figure 8: Concentration profile (c=0.1 ; 0.3 ; 0.5 ; 0.7 ; 0.9)

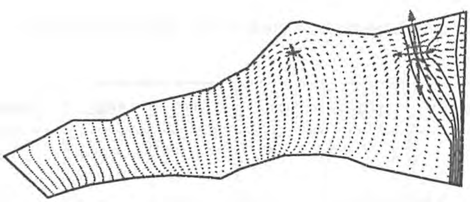

Figure 9: Isochlors and velocity field on the bottom of the aquifer (convergence of velocity areas indicate the pumping well locations).

5-2. The Chaouia coastal aquifer (SEAWAT code)

The Chaouia coastal aquifer is located south of the Casablanca city (Morocco), and considered among the main sub-atlantic coastal aquifers in Morocco with an area of 1200 km^2. The only water resource available in the Chaouia plain comes from the shallow groundwater. This favourable situation has increased irrigation by pumping, and contributed to the agriculture development in this plain. But, this development of pumping has induced environmental problems, such as: over-exploitation of the aquifer with a groundwater table decrease of 0.6 m/yr; progressive dry out of some aquifer levels; salt water intrusion; degradation of the groundwater quality; and significant increase of the abandoned pumping wells. For this, a mathematical model in transient conditions, based on the SEAWAT code, has been developed to study groundwater flow and salt water intrusion in this aquifer. Different management scenarios have been simulated to provide the managers with a prediction tool that could help in decision making for quantitative and qualitative groundwater management in this groundwater system. The simulation results with respect to development of water resources in this coastal aquifer showed that surface water is required to protect the irrigated area and to restore the abandoned exploitation on one hand, and to improve water quality in the area which is already contaminated by seawater intrusion, on the other hand.

Table 1 illustrates the results of different water balance terms between 1965 and 2001, as obtained from the transient simulations. The results show that the intensive groundwater pumping, especially between 1965 and 1985, resulted in less storage in the aquifer which reached 24 Mm3 in 1985. As a consequence, seawater intrusion advances inland and continues to progress until 1995.

In order to study the seawater intrusion effect on the south-western part, a model of transverse section with a refined mesh has been developed. The objective of this local model is to simulate the extent of the saltwater intrusion with a finer spatial resolution in two dimensions. The model results will be of great importance for the management policy at the local level.

The mesh cells dimension is reduced to 100 m along the x-axis for the same simulation period adopted for the global model.

Table 1: Calculated mass balance for the transient simulations.

Water balance terms (Mm^3/yr)	**1965**	**1970**	**1975**	**1980**	**1985**	**1990**	**1995**	**2001**
Inflow storage variations	3,86	15,67	23,19	15,27	24,52	6,92	5,42	0,53
Seawater Intrusion	0	0	0	0	0,40	2,13	4,05	1,10
Recharge by precipitations	64,17	56,37	55,92	53,59	33,95	43,48	40,23	48,16
Lateral flow	5,86	5,53	4,56	3,72	3,08	2,81	2,67	2,37
Inflow from Oum Er Rbia river	0	0	0	0	0	0,06	0,15	0,14
Total inflow	**73,89**	**77,57**	**83,67**	**72,58**	**61,95**	**55,40**	**52,52**	**52,30**
Outflow storage variations	0,34	0,03	0,06	0,37	0,56	8,18	3,83	4,75
Discharge to Atlantic Ocean	41,90	34,05	23,71	23,23	13,60	10,12	8,18	10,30
Agricultural and domestic abstraction	16,36	32,79	51,93	41,71	42,43	31,12	34,65	30,62
springs	1,11	0,77	0,60	0,45	0,28	0,47	0,47	0,64
Evaporation	13,09	8,95	6,46	5,96	4,57	5,11	5,01	5,6
Discharge to Oum Er Rbia river	1,08	0,98	0,92	0,87	0,50	0,40	0,37	0,38
Total outflow	**73,89**	**77,57**	**83,67**	**72,58**	**61,95**	**55,40**	**52,52**	**52,30**
Error %	-0.01	-0.003	-0.0058	-0.0089	-0.0005	-0.0073	-0.014	-0.0078

Figure 10 illustrates the results of this transverse model in transient conditions. These show that seawater intrusion started in 1980-85 by contaminating the aquifer on 100 m from the coast line; and the estimated extent of the seawater intrusion wedge reaches 1300 m in 2001.

The numerical model is also applied to test the response of the aquifer of two planning scenarios for a period of 40 years (2001-2040). The first one is the design of an irrigation project from surface water and stopping groundwater withdrawal in the south-west sector; and the second scenario is a continuous pumping from the aquifer. It is predicted that the first scenario will reduce considerably the quantity of seawater intrusion and improve the groundwater quality, although in a slow manner in the south-western sector. However, the results from the second scenario will induce a considerable quantity of seawater intrusion, and its extent progressed more into the inland aquifer and will reach the north sector of the coastal part. More details on the results of this study can be found in Lakfifi et al. (2004). The present case study of the Chaouia coastal aquifer is an example of a pilot study to develop also for several coastal aquifers threatened by this phenomenon, as Morocco is extended over more than 3500 km of coasts.

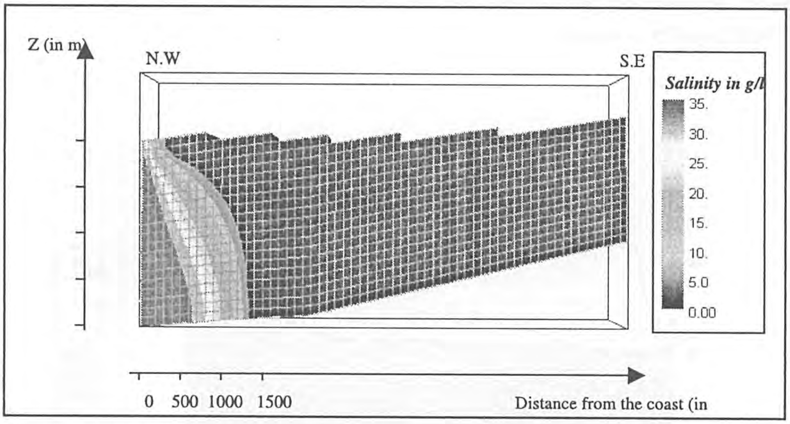

Figure 10: Result of the cross sectional simulation model in 2001.

5-3. Numerical modeling of seawater intrusion in the Sahel aquifer of the Atlantic coast of Morocco (CODESA-3D code)

The Sahel region, of about 100 km in length, is an important agricultural plain where groundwater is heavily used as an irrigation supply. In 1994 a study to evaluate the impact of pumping on the salinization of the aquifers and to define a proper exploitation scheme, was completed by the regional hydraulic department in collaboration with FAO. A hydrogeochemical database was built up using data collected from a network of 30 wells. These data were used to implement a 2D groundwater flow model using the USGS MODFLOW software (McDonald and Harbaugh, 1988). To overcome some of the limitations of this earlier study, among which the assumption of a static salt-freshwater interface coinciding with the aquifer bottom which over-estimated the freshwater outflow to the sea, simulations using CODESA-3D model was undertaken. The model implementation allows a more realistic representation of the hydrodynamics of the aquifer system, considering also the presence of a mixing zone between the freshwater and the seawater.

This study describes simulations being conducted on a series of cross-sections perpendicular to the coast and corresponding to the geophysical profiles performed in a previous study, have been analyzed. Along these profiles measures of the depth of the salt/freshwater interface were available. The first simulation, covering the period 1950-1992, is calibrated to the water table levels and to the observation data and flow simulations. Figure 11 shows the comparison results in 1950. The darcy velocity field is also shown, which denotes at the ocean side on the left boundary of the domain an upper outlet of freshwater into the sea and, correspondingly, a lower inlet of seawater into the aquifer. Figure 12 compares the measured saltwater-freshwater interface with the computed relative concentration isocontours of a 42-year transient coupled flow and transport simulations.

The study on these selected cross-sections has pointed out the important role of an adequate grid density (20 m) and a good estimation of the unsaturated zone and transport dispersivity parameters for the characterization of the saltwater intrusion in the Sahel aquifer system.

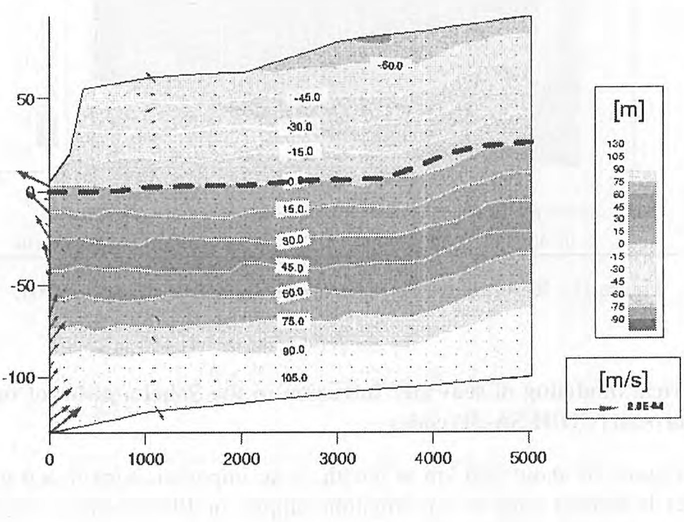

Figure 11: Comparison between observed water table level (black dashed line) and computed pressure head ψ [m] isocontours for profile 4w. The computed Darcy velocity field [m/s] is also shown (blue arrows).

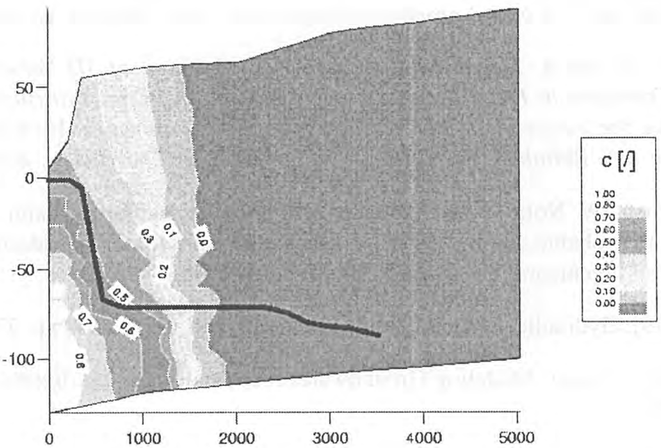

Figure 12: Measured salt freshwater interface (black line, from geophysical investigations) and computed isosaline c [/] contours.

6. Conclusion

An overview of modelling seawater intrusion in coastal aquifers is presented. Some analytical solutions and laboratory model, either based on sharp or variable density approaches, have been also outlined as to serve benchmark problems for testing developed numerical codes. However, the question of which type of physical approach is appropriate to deal with seawater intrusion in coastal aquifer, must be clarified, especially when studying field cases. Sharp interface model or the disperse interface model? This depends on the scale of interest: if near-coast, the effects and variations in salt concentration are important, then dispersion features of the interface are important; if far-coast and the regional monitoring aspects are important, then more interested to investigate the distance and depth of the interface, and so the sharp interface approximation is preferred.

Recent numerical codes based on a 3-D finite elements and finite differences, developed to predict the location, the shape and the extent of the moving interfaces in coastal aquifers involving unconfined or confined flow have been also presented. Some field applications have been studied using recent numerical codes in order to assess groundwater resources and to test the groundwater system response to planning scenarios to help the managers in making decision for rational groundwater management. Examples are taken from Morocco, where models were applied on some coastal aquifers to simulate groundwater flow and to study the impact of irrigation and increasing pumping well rates used for water public supply. The site description and the simulation results are presented in separate papers published previously (Aharmouch and Larabi 2004, Hilali and Larabi 2004, Lakfifi et al., 2004).

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On Groundwater models and the need of sufficient and reliable data, examples, dependencies and interrelations

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ON GROUNDWATER MODELS AND THE NEED OF SUFFICIENT AND RELIABLE DATA, EXAMPLES, DEPENDENCIES AND INTERRELATIONS

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ABSTRACT

The quality of the results of groundwater simulation models directly depends on the availability of a sufficient and reliable data base. Generally, this precondition is often not completely fulfilled in model investigations in many Arab countries, which strongly affects model calibration and leads to uncertainties and errors in the modeling results. The recent behavior and the future development of the investigated groundwater system will incorrectly be described. Such models can not be used for groundwater management purposes and reduce confidence in this powerful management tool. The problems in the data base are manifold. In some cases, the data base is too small for developing an acceptable model to describe the groundwater system. In other cases, the spatial and temporal distribution of the available data is disadvantageous for building an accurate hydrogeological structure. Furthermore, even if the quantity of the data is sufficient, there is very often a lack in quality. The quality problems come e.g. from measurement errors in the field and in the laboratory, unaccounted heterogeneities, wrong combinations and interpretations of data, or simple typing errors. Often quality assurance procedures are missing. To overcome some of these errors, groundwater models should be used during the whole investigation process of a groundwater system, from the beginning, simplified models would give indications for missing data and important processes. Later on, the quality of data can be checked, e.g. during the development of a structural model and during the calibration phase. The interrelation between model results and data base can therefore be used as one guiding principle for an investigation program. These interrelations and also dependencies between the modeling results and the data base are illustrated by some examples and case studies.

Keywords: Groundwater modeling, Uncertainty analysis, Groundwater management, Data quality, Model conceptualization.

1. Introduction

Groundwater simulation models represent powerful tools for the assessment, development and management of groundwater resources. However, they have high requirements regarding data quantity and quality. In order to manage their limited groundwater resources appropriately, the Water Authorities in the Arab region need this efficient tool to help them in taking the most suitable (sustainable) management decisions. However; there is always a significant amount of uncertainty associated with the practice of groundwater modeling. This uncertainty can be associated with the conceptual model or with the data and parameters associated with the various components of the model. Some model parameters such as hydraulic conductivity and recharge are particularly prone to uncertainty. Calibrating a model to a rich set of observation data (monitoring wells, stream flows, etc.) may reduce this uncertainty. However, calibration data are often scarce and even a well-calibrated model may have a high level of uncertainty (EMRL, 2003).

This paper will present few case studies where the lack of data constrained the development of reasonable groundwater management decisions.

2. The Issue of Observation measurements

Water level is the basic input in a groundwater model. It is used for calibrating and verifying the model. Hence, any error in the measurements will mislead the process of model calibration and will result in an error in the related hydraulic property of the aquifer. Moreover, in seawater intrusion models, these water level measurements are of even more importance sine they will define the axis and extent of the intrusion. The results derived from any model using these measurements will have un-quantified uncertainty.

a. Quality of water level measurements: Khabour Basin (ACSAD, 2003)

In a model developed for a confined aquifer located in northern Syria, the piezometers used were not all well constructed in the sense that they do not all measure the water level of the studied aquifer. The piezometers were sometimes not isolated at the upper aquifers. This has resulted in wrong unrealistic measurements. This is a common problem in most of the cases in the region and there are some ways to overcome or mitigate such problem. Luckly, there were several well constructed piezometers in the area which were used to correlate their readings with the hydrogeological conditions (Fig 1).

The piezometers were grouped according to the hydrogeological properties and the correlation between the readings of each individual piezometer and its group average readings was established. This was very helpful in defining which piezometer has low correlation and therefore has lower confidence in measurements (Unless if there were any noticed practices could lead to such uncorrelated measurements) (Figure 2c). The problem was worsened by the bad spatial distribution of the piezometers inside the study area. There were many gaps in the area which required construction of piezometers (Figure 1). A GIS layer was constructed showing the well density in the area (Fig 2a). In addition, there were some "hot" areas where the water authority wanted to have a "closer" look (Figure 2b).

From the above layers and using GIS tools it was possible to sum all the layers and build a layer which shows the water authority where are the most important places to start constructing a new set of piezometers (Figure 3).

b. Quantity of water level measurements: Hasia Basin (ACSAD, 2004)

It is difficult to define the sufficient number of observation wells. This is highly depending case-specific; i.e. the scale and the objective of the study, the level of aquifer exploitation, the complexity of hydrogeological condition, the existence of tectonic structure, transient or steady state conditions, ...etc. Insufficient number of observation wells could also lead to deficiencies in the formulation of the conceptual model. In one case the authorities planned to build an industrial complex in an area that has a very complex tectonic structure. The area was affected by two major faults and several small lateral faults (Figure 4).

The low number of observation wells (in addition to a poor knowledge of the hydrogeological conditions) prevented the accurate representation of the hydraulic functions of the faults. Accordingly, and by using geostatistical analysis one can end with several water table maps with all satisfying the points of measurements in the field but with different spatial distribution (Fig. 5). The complex site was close to conjoint point of the two major faults. The cone of depression resulting from any additional pumping to meet the requirement of the complex will definitely be affected by the actual function of the faults. It was very hard to give the authorities the amount of water that alfild definition and ice)they can pump safely. The study was used to guide the authorities to the places where more observations are required and showed them the inadequacy of the available data.

3. The issue of model conceptualization

The foundation of model analysis is the conceptual model. Conceptual models have many uncertain features because data are never exhaustive and contain inconsistencies. It depends strongly on the geological and hydrogeological conditions which are rarely known accurately. Addressing the uncertainty often requires posing several conceptual models (Carrera, 2005). Different models can be compared and judged to choose the "appropriate" one. Stochastic analysis has also been considered to be an effective method of analyzing heterogeneous subsurface. Specific advantages of stochastic analysis are that a few selected statistical parameters of the subsurface properties, such as mean and variability, can be used to determine the overall variability of key subsurface processes. However, in most field-scale problems, it is important to know the expected variability of the processes.

a. Aquifer geometry: Ras el Jebel Basin (ACSAD-BGR, 2004)

A good definition of the aquifer's geometry is always a common problem in the region. The high cost of exploratory wells constrains drilling new wells. In most cases the aquifer geometry defined according to the expert knowledge of the hydrogeological conditions. This practice will definitely increase the uncertainty level of the model results especially in thin, highly pumped aquifers. The problem is aggravated in coastal unconfined aquifer where the depth of the aquifer base below the sea level plays a major role in determining the amount of water flow to and from the sea.

A hydrochemical groundwater model was developed for a coastal aquifer located in northern Tunisia to find out the reasons for the increasing of groundwater salinity. The study showed how much the model is sensitive to the quality of input data especially to the aquifer geometry. The aquifer base is outcropped in some places just before the coast which prevents sea water intrusion, and in other places inside the sea causing intrusion of sea water (Figure 6). Combining insufficient data with errors introduced by interpolation, the simulated hydraulic situation could not be matched with the available data. The quality and quantity of the input data should be revisited. The model can't be used to make some prognoses unless better determination of the aquifer geometry is done.

b. Boundary conditions: Lower Euphrates Basin (GCHS, 2000)

Boundary conditions have a great influence on model results. Choosing the wrong boundary will in most cases ends with misleading results. Boundary condition could be physical boundary such as river, lake or sea, and sometimes are hydraulic boundary. The latter is the most vulnerable boundary and can be changed with time.

An example is the study of the lower Euphrates valley. The valley is formed by Euphrates deposits ranging from torrential (coarse) to fluvial (fine) alluvium. The hydrogeological investigations revealed that the basin is surrounded with different physical boundaries. River boundaries are at the south west and a no-flow boundary at the north east (Fig. 7). In a previous study (GERSAR, 1984), the river was considered as specified head boundary (first degree boundary). Such boundary ignores any hydraulic resistance to groundwater flow posed by the river bed. After 15 years, more boreholes were drilled close to the river. The variations in water level in these boreholes showed poor correlation with the variations in the river stage level. This implies that the boundary should have been taken as third degree boundary condition. Using this boundary reduced the function of the river as a natural drainage to groundwater. The natural flow toward river reduced from 30 % of irrigation water to 10%, which better explained the rising water level in the area.

4. Conclusion and Recommendations

Dealing with uncertainty is an integral part of simulation modeling practice. Acknowledging uncertainty in both the conceptual model and hydraulic parameters is required. Predication results should always been judged accordingly. Using groundwater models during the whole investigation process of a groundwater system, from the beginning, simplified models would give indications for missing data and important processes. Afterwards, the quality of data can be checked, e.g. during the development of a structural model and during the calibration phase. The interrelation between model results and data base can therefore be used as one guiding principle for an investigation program.

The ability of a calibrated hydraulic property field to represent the true field is limited. The less the information content of the data set used for calibration, the more "smooth" (or "piecewise smooth" as in zones) and less detailed our calibrated field become (Moore & Doherty, 2004).

To overcome the inevitable uncertainty involved in groundwater modeling, resulting from the uncertainty in model hydraulic parameters and severe spatial heterogeneity of the aquifer parameters, in addition to the problem of non-uniqueness in model solution, a stochastic modeling approach might be very useful. The advantage of the stochastic approach, as opposed to the traditional deterministic approach, is in the incorporation of the uncertainties faced in the modeling procedures within the decision process, and the ability of conducting risk assessment by quantifying the probability of violating pre-specified management constraints. However, deterministic models lead to improved statistical models (Vogel,1999). Physically based model of groundwater flow can suggest variables and the functional form for statistical models.

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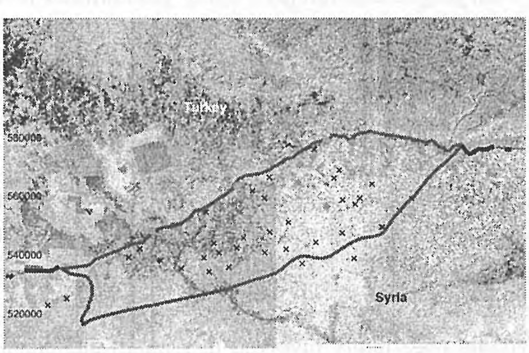

Fig 1: Study area. Khabour river in blue, red circles are the standard piezometers, black dots are the observation wells.

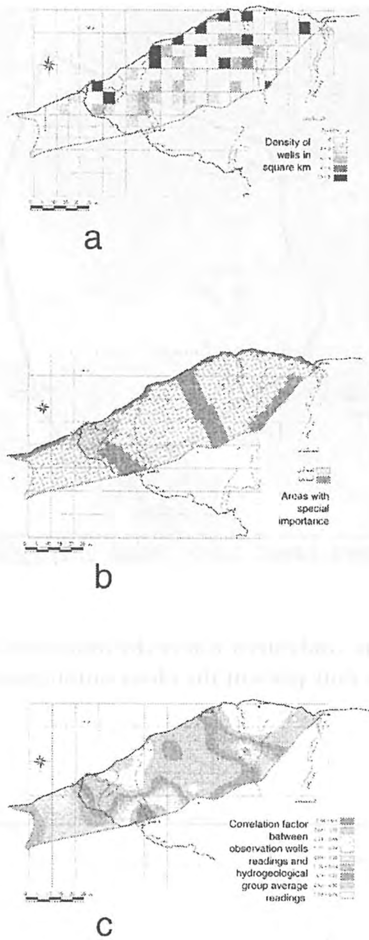

Fig. 2: GIS layers used in defining the important places for new sets of piezometers

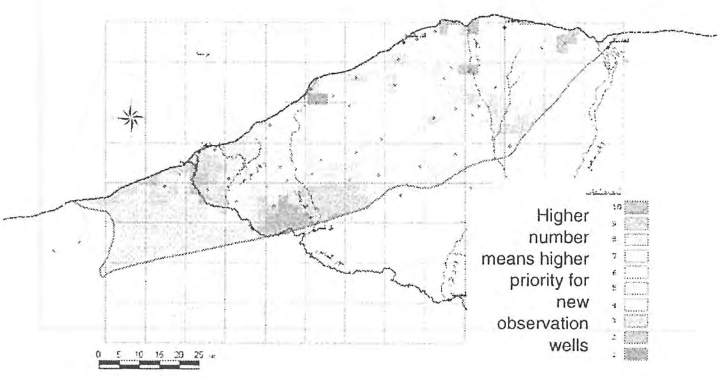

Fig. 3: The most important places to start constructing a new set of peizometers .

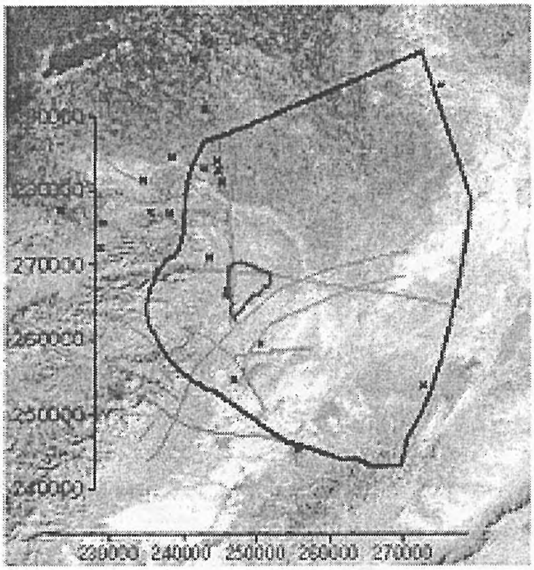

Fig. 4: Satellite image of the study area where the industrial complex in brown and the faults in red. The black dots present the observation points.

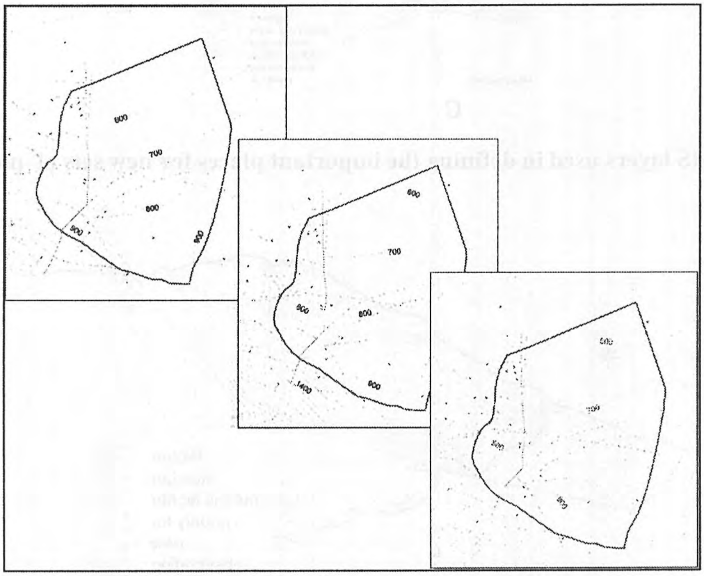

Fig. 5: Water table maps drawn for different faults' function.

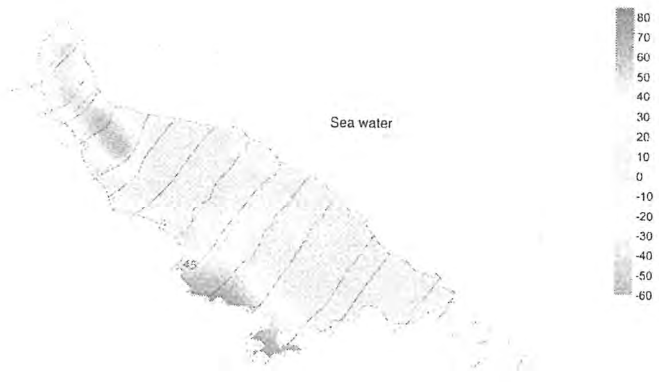

Fig. 6: Geophysical profiles show the aquifer base levels.

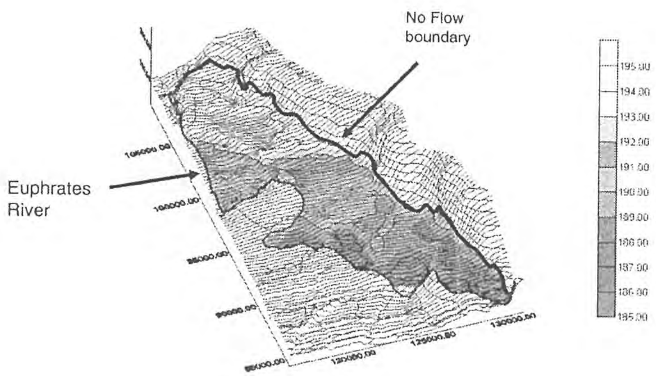

Fig. 7: Lower Euphrates valley where the blue line is the river. The color scale is for land surface elevation.

Simulation of groundwater conditions in the vicinity of wadi Al-Jizzi Dam, Sultanate of Oman

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SIMULATION OF GROUNDWATER CONDITIONS IN THE VICINITY OF WADI AL-JIZZI DAM, SULTANATE OF OMAN

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ABSTRACT

The renewable water resources in the Sultanate of Oman are limited due to the scarcity of rainfall. Like other arid and semiarid regions, rainfall events are characterized by their short durations and high intensities. Flashfloods are thus developed and considerable amounts of surface water runoff are generated. Many dams have been constructed across the main wadis in the mountainous areas of the Sultanate of Oman over the last two decades. These dams are built to collect the surface water runoff, recharge the groundwater systems and mitigate the seawater intrusion problem in the coastal aquifers. Eighteen dams have already been constructed. The main objective of this paper is to study the groundwater conditions in the area of Wadi Al Jizzi recharge dam. Physical, geological, hydrological and hydrogeological settings of the area have been identified. All available records for groundwater levels and trends have been assessed. The USGS finite difference groundwater model "MODFLOW" has been employed to simulate the groundwater conditions in Wadi Al-Jizzi. The study domain (30 km x 30 km) was discritized into a total number of 22500 regular cells. Each cell has dimensions of 200m x 200m. Various types of boundary conditions were applied to accurately simulate the field conditions. The aquifer was assumed to be homogeneous and the flow in the aquifer was assumed to be fully horizontal. The model parameters were calibrated for the period 1985 to 1994 until a good match between the observed and simulated groundwater levels was obtained. The model was then validated for the period 1995 to 2002. It is concluded that the Wadi Al Jizzi dam has increased the annual recharge by about 36% as compared to the conditions prior to the construction of the dam.

Keywords: Wadi Al Jizzi, dam, groundwater recharge, numerical modeling, MODFLOW.

1. Introduction

Water is the most precious resource in arid and semi-arid countries including the Sultanate of Oman. In such countries, groundwater is regarded as the major, if not the only, source of renewable water. However the long-term yield and sustainability of such aquifers should be periodically evaluated. Annual recharge of groundwater resources, in such areas, is generally small but groundwater levels may also recover very quickly during wet years.

The Sultanate of Oman occupies the south-east corner of the Arabian Peninsula, Figure 1. The coastline extends for about 1,700 km from the Strait of Hormuz in the north to the borders of the Republic of Yemen in the south occupying a total land area of approximately 309,500 km^2. It overlooks three seas: the Arabian Gulf, the Gulf of Oman and the Arabian Sea. Oman borders Saudi Arabia and the United Arab Emirates in the west, the Republic of Yemen in the south, the Strait of Hormuz in the north and the Arabian Sea in the east. The total population of Oman is about 2.4 million (MNE, 2000).

The topography of Oman consists of plains, desert, mountain ranges and wadis. Mountain ranges occupy 15% of the total area and extend for about 700 kilometers from the north to the south with a width varying between 30 and 130 kilometers (Al-Ghilani, 1996). The two main mountain ranges are the Hajar range, running from Musandam to Ras al Hadd, and the Qara range in Dhofar, which attracts the light monsoon rains during the mid-summer months. Around 82% of Oman area is desert.

There are considerable variations of climatic conditions within the country due to its size and configuration of its topography. Summer starts in May and ends by October while winter extends from November to April. The climate differs from the coastal areas to the interior ones, but is generally described as hot and humid. Rainfall is generally light and irregular. The average annual rainfall varies from less than 50 mm in central Oman to more than 300 mm in the Northern Oman Mountains (MWR, 1995).

Due to the increase in population and the associated increase in agricultural and industrial activities groundwater abstraction from the different aquifers in Oman has increased tremendously since the mid 1970. This over exploitation of the groundwater resources has led to a considerable decline in the subsurface water levels and hence affected the water balance in the interrelated hydrogeological systems. In order to sustain the groundwater resources in the country, the government has constructed eighteen dams across the main Wadis in the Sultanate of Oman since 1986. Two types of dams were constructed in Oman, storage dams and recharge dams. Storage dams are designed to store water during times of excess flow, so that water can be used when there is a lack in natural flow for irrigation and domestic uses. Recharge dams are designed to store the surface runoff and facilitate its infiltration to the subsurface. These dams are mainly built to recharge groundwater systems and minimize seawater intrusion in coastal aquifers. The efficiency and performance of the constructed dams as an effective tool for groundwater recharge need to be assessed.

This paper is devoted to the assessment of the efficiency of the recharge dam in Wadi Al-Jizzi. To that end, geometric, geological and hydrogeological conditions of the aquifer system in the study area have been identified. Trends of groundwater levels during the last two decades have been presented. The USGS finite difference groundwater model MODFLOW has been employed to simulate the groundwater conditions in Wadi Al-Jizzi and assess the efficiency of the dam in recharging the aquifer system.

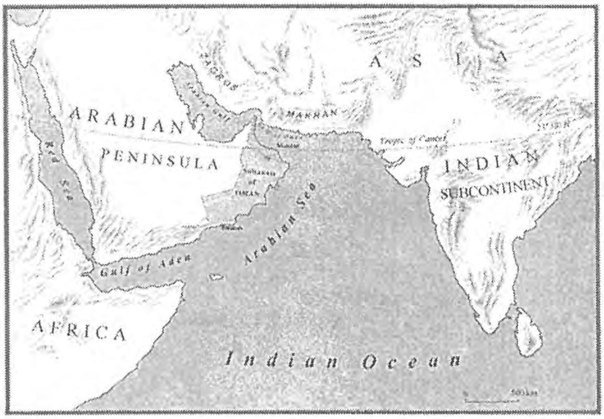

Figure 1: Location map of the Sultanate of Oman

2. Physical Setting of Wadi Al-Jizzi

Wadi Al-Jizzi is one of the largest catchment areas, among 20 other catchments, in the north of the Batinah area which is located in Sohar town about 245 km northwest of Muscat, Figure 2. It consists of: i) an upper mountains catchment area on the Hajar Gharbi mountains; and ii) a lower catchment in the Batinah plain. The principal Wadis that drain to Wadi Al- Jizzi are: Wadis Kitnah, Ghalil, Hayl, Lasail, Barghah, and Yanbu. The total drainage area of Wadi Al-Jizzi is about 1055 km^2.

Developments in Wadi Al-Jizzi catchment occur mainly on the coastal plain between the main highway and the Gulf of Oman. Agriculture activities have increased significantly in the last 3 decades due to the introduction of irrigation pumps and modern farming techniques. Recent assessments indicated a significant water deficit associated with saltwater intrusion in the coastal area. Wadi Al-Jizzi Dam was built in 1989 with a total reservoir capacity of $5.40 x 10^6$ m^3 to recharge the aquifer of Wadi Al-Jizzi (Cansult, 1998).

Wadi Al-Jizzi dam is estimated to conserve about 3.5xl0 m^3/yr of surface water runoff from discharging to the sea (JICA, 1986). Like other dams in Oman, one of the most important problems in Wadi Al-Jizzi dam is the accumulation of silt in the reservoir which significantly decreases the rate of water infiltration down to the groundwater and causes clogging of culverts. It is also noted that there is an excessive seepage that is encountered when the dam is filled with water. The dam is 19 m in height and this high hydraulic head would create a good potential for seepage beneath the structure. This problem was studied by Sir Mott MacDonald and Partners in the year 1990.

Additional field work was conducted in 1998 to cut off the seepage beneath the main body of the dam and to prevent further loss of fine soil material in this area. The reservoir of the dam has not been completely filled with water since that time and it is not known as to whether the seepage has actually been reduced or not.

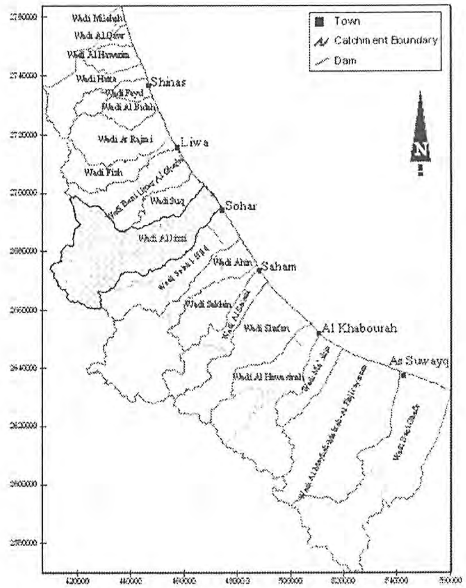

Figure 2: Northern Batinah catchments map.

3. Local geological conditions

The Northern Oman Mountains contain an unusual sequence of ophiolitic rocks derived from the oceanic crust and mantle (MWR, 1995). Al-Batinah plain is divided into two main zones with distinct characteristics; the piedoment zone which consists of a series of alluvial terraces and the coastal plain zone which consists of alluvium deposits with a thickness of 600 m.

Wadi Al-Jizzi consists of the following three hydrogeological units; the impervious formations, terrace deposits, and alluvial deposits (JICA, 1985). The alluvial deposits of Quaternary age overlie the bedrock or clays and marls, where present. These deposits consist of silts, sands, gravels and pebbles. Gibb and Partners (1976) presented the following general classification for the coastal sediments which is applicable to Wadi Jizzi:

1. Upper Gravels: these are beds of clean gravel and sand with boulders
2. Clayey Gravels: these layers contain clays and marls but with some thin layers of clean gravels; and
3. Cemented Gravels: this unit is characterized by white clays and marls and carbonate cement with some thin beds of cleaner gravels.

At the dam site, the overburden includes alluvial terrace deposits composed of sands, gravels, and boulders. The boulders derived from the ophiolites are highly weathered. The base of the upper terrace deposits are formed by well-cemented conglomerates. The wadi channel is 650 m wide at the dam. The upper three to five meters of soil is composed of recent alluvial deposits (unweathered poorly graded gravels and boulders). Underlying the wadi deposits are older terrace deposits which, in turn, overlie the bedrock. The bedrock consists of antigorite/serpentine on the left bank and limestone on the right.

4. Aquifer System and Hydraulic Parameters

The Batinah alluvial aquifer is one of the most important aquifers in the Sultanate of Oman. It supplies water for the most densely populated, cultivated and industrialized areas. In recent years, overexploitation of this aquifer has resulted in a drastic lowering of the groundwater table, leading to seawater intrusion into the coastal alluvial aquifer. Many monitoring wells are distributed along the catchment of Wadi Al-Jizzi, Figure 3.

The main aquifer within the coastal plain is formed of alluvial deposits. The thickness of the alluvium in the upper catchment is typically less than 20 m. The composition ranges from clay to boulder and weakly to strongly cemented. Near the coast in the Sohar area, the alluvium thickness is greater than 237 m northeast of the Tertiary limestone. The thickness of the alluvium and the aquifer potential is not well known in the northwest of Sohar because of limited deep drilling in that area.

The hydraulic characteristics of the aquifer are important in determining its ability to store and transmit water. Transmissivity values were estimated from pumping tests performed on a number of boreholes in the catchment. Based on former studies the transmissivity ranges between 126 and 7000 m^2/d in the inland area and between 500 and 1000 m^2/d in the coastal zone. The hydraulic conductivity, based on the limited number of tests, varies between 25 m/d to 450 m/d. The storage coefficient showed a wide variation, ranging from 1×10^{-4} to 6×10^{-2} (Cansult, 1996). A storage coefficient of 0.05 was used by JICA based on a test nearby Wadi Salahi. Tests of the DEO wells showed a much lower storage coefficient (ranging from 8×10^{-7} to 1×10^{-5}) suggesting semi-confined conditions in the coastal plain east of the gas pipeline (Cansult, 1996). The thickness of the permeable alluvium varies from about 30 m at the dam site to less than 10 m further downstream crosses the wadi near well NJ-3, Figure 3, and significantly increases towards the coastal plain. The depth to bedrock at the coast is known to be more than 240 m in the Sohar-Saham area (IRI, 1978). For more details on the hydrogeological parameters of Wadi Al-Jazzi, reference is made to Al-Kindi (2004).

Based on the review of the groundwater levels since 1989, in the catchment of Wadi Al-Jizzi, it is concluded that there was a minor change in the groundwater level between the years 1989 and 2001. However, a remarkable change was observed in the year 2003. Contour maps revealed a change in groundwater levels mainly in the eastern part of the catchment near the coast (almost 7 km inland from the sea boundary). Based on the comparison of the groundwater levels in wet and dry years, it was found that groundwater levels respond quickly to heavy rainfall events. Figure 4 presents a contour map for the groundwater level in the study area for the year 2003.

5. Groundwater Simulation using MODFLOW

5.1 Study domain and boundary conditions

The study domain has been selected from the end of the impermeable bedrock to the eastern coast line. The entire western part of the upper catchment is not included in the model domain as most of the western part of the catchment is covered by impermeable rock which is termed as no flow boundary in groundwater modeling. Recharge component includes the surface runoff from the upper catchment. The through flow from the upper catchment has been considered by constructing a general head boundary. The selected model area extends from 445000m to 475000m easting and 2672700m to 2702700m northing in UTM coordinate system, Figure 5.

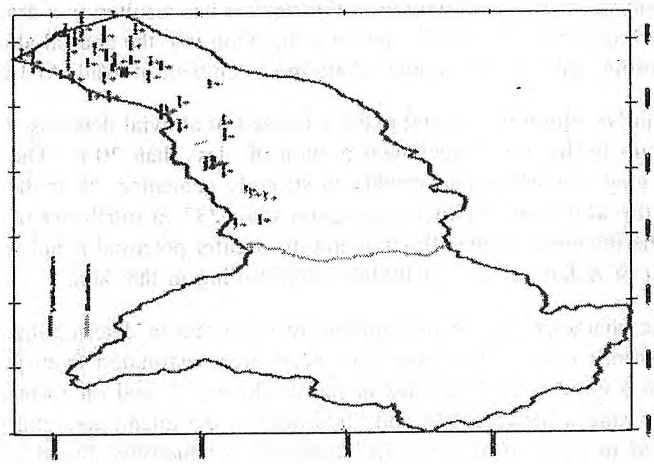

Figure 3: The distribution of monitoring wells in Wadi Al-Jizzi catchment

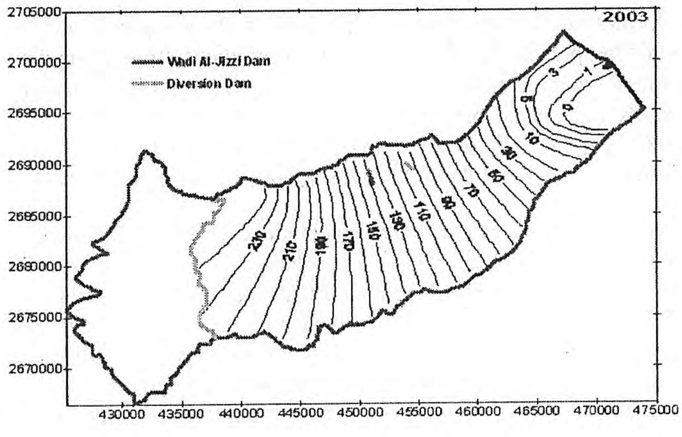

Figure 4: Contour map of groundwater levels in 2003.

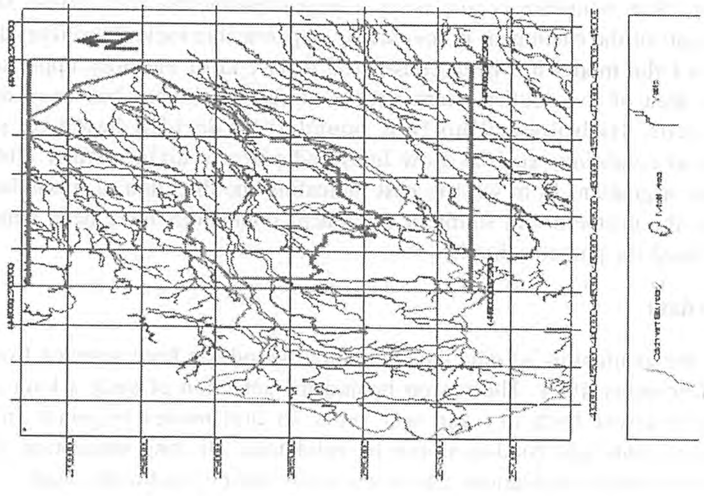

Figure 5: The study domain.

The study area has been divided into 200m by 200m grids resulting in 150 columns, 150 rows and 22500 cells per layer. Cells in the grid which fall outside the catchment are designated as "inactive". The impermeable rocks in the upper catchment are designated by inactive cells. These inactive cells do not contribute to groundwater flow and remain out of the model simulation. The flow nets show a direction of groundwater flow from west to east. The model needs not to be oriented, i.e. 0 orientation angle has been used. Local origin of the model and base map of the study area has been selected at UTM coordinates (445000, 2672700). All digital maps have been transformed by subtracting this constant offset.

Model boundaries represent the external hydrological conditions. At the physical boundaries they reflect interaction with the outside world like levels; flows etc. while inside the study area they reflect the hydrological stresses like recharge, abstractions and pre-defined levels in the watercourses (Muzahidul, 2002). The main consideration for the selection of the model boundaries is to obtain a set of boundaries that are not affected by the change in hydrological conditions in the study area.

A constant head has been applied to represent the shoreline boundary in the top layer along the coast of the Gulf of Oman in the northeastern part of the catchment. Considering the seawater level as reference level the saline groundwater head is at 0 level. Although, the difference in density of saline and fresh water appears to be small, they have a significant effect on piezometric heads and thus on the groundwater system. Hence, the head is adjusted on the basis of the Badon Ghijben (1889)-Herzberg (1901) principle. The pressure of saline water body is equal to the pressure of the fresh water body. This satisfies the prevailing local aquifer conditions. Following the above principle, the saline water head is adjusted (the centre of the boundary cell of each layer). For r_s=1025 kg/m^3 and r_f=1000 kg/m^3, the relative density difference is a=0.025. Hence, the adjusted head for any cell becomes $h_f = (1 + a)$ H.

Two types of no flow boundaries have been assumed, physical and hydrological. Physical no flow boundary occurs when a large impermeable rock exists. Most of the upstream part of the catchment is covered by impermeable rock. Therefore, the western boundary of the model has been considered from end of the hilly upper catchment. The rock area of the southwestern corner of the catchment has been defined by inactive cells. Hydrological no flow boundary is decided based on prevailing hydrological conditions such as flow lines and phreatic divide. Water table contour map shows a gradient from west to east indicating the direction of groundwater flow. Therefore, the northern and southern catchment boundaries have been considered as no flow based on phreatic divide.

5.2. Input data

Based on the availability of data the simulation period has been selected from January 1985 to December 1994. The reason behind the selection of such a long simulation period is to cover both dry and wet years so that model response in different hydrological years and conditions can be validated. The long simulation period also stabilizes the initial fluctuations due to errors in starting hydraulic head.

To incorporate the variation of hydrogeological stresses over time, the 10 years simulation period has been divided into 198 number of stress periods. The length of the stress periods have been decided based on the wadi flow. When the wadi flows the stress period length has been chosen equal to the number of days of the flow while the longest stress period has been chosen to be 1 month during the no flow period.

The contour lines of the aquifer thickness are presented in Figure 6. Once the layer elevations have been identified, the next step in model setup is to define aquifer parameters like Hydraulic Conductivity (K_x, K_y, K_z), Specific Storage (S_s), Specific Yield (S_y), Porosity etc. Initially, model area was divided into zones according to different geology. Data in Cansult (1998) was used as initial estimates of aquifer properties. Recharge is a very important component of the hydrogeological cycle. Most often there is no direct way of recharge measurement. It depends on soil characteristics, surface topography, intensity and duration of precipitation, wadi flow, irrigation return etc. For the present study rainfall and wadi flow have been considered as recharge components.

Recharge from each of these components has been estimated based on the geology and wadi flow zone. Therefore, the study area has been divided into 20 zones based on the geology and wadi flow. A different infiltration factor has been used for each recharge zone. These infiltration factors have been used as calibration parameters to adjust the estimated recharge. It was assumed that the dam reservoir has higher recharge factor. Therefore, a separate zone has been created around the dam area.

Most of the abstraction takes place in the downstream part of the catchment. According to National Well inventory database the study area contains 3667 operational abstraction wells to meet a yearly net demand of 26.87 Mm^3. This net water demand was considered as yearly abstraction. The yearly abstraction was then distributed between summer and winter. Monthly abstraction rate has been used for 6 SDO wells.

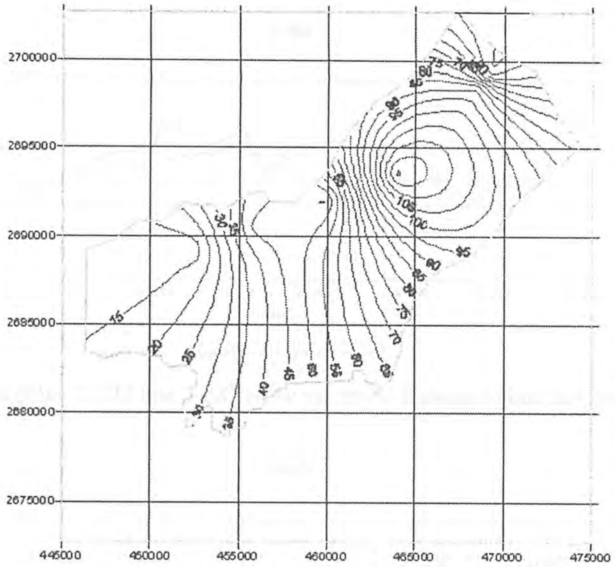

Figure 6: Aquifer thickness contour

5.3. Model calibration

Calibration is a trial and error method where the initial estimates of the model parameters are adjusted to produce a better match between simulated and observed conditions. A calibration target is a point in space and time where one of the model dependent variables has been measured.

Arial calibration has been done manually for the end stress period (December 1994). Matching the end stress period also reduces the difference in time series. In addition to hydraulic conductivity and specific yield, recharge, constant head inflow and through flow from the upper catchment have also been calibrated at this stage to give a reasonable estimate of the components.

Calibration statistics are computed by first calculating the error associated with each target and then calculating simple statistics on the error of targets. The error is called a residual and is computed by subtracting the model-computed value (head, drawdown, concentration, or flux) from the target value. Negative residuals indicate that the model is calculating the dependent value too high and a positive residual is where the model value is too low. Figure 7 (a and b) presents a comparison between the observed and calculated water levels in observation wells QA-1 and DE-4. The agreement between the observed and calculated levels is good.

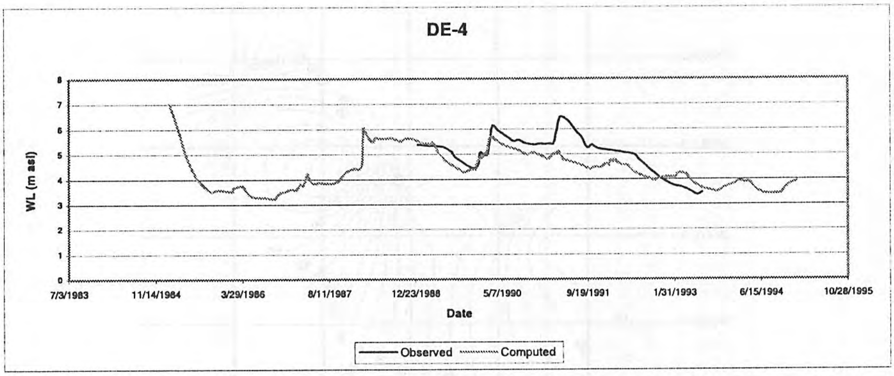

Figure 7: Observed and computed levels for wells OA-1 and DE-4, calibration period.

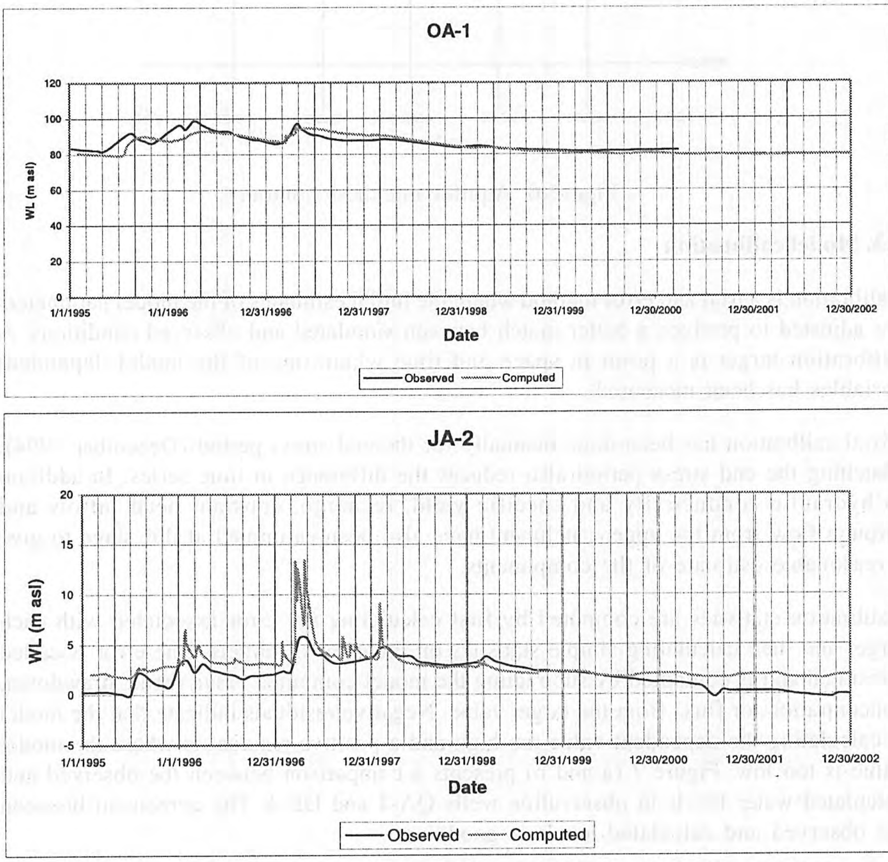

Figure 8: Observed and computed water levels for wells OA-1 and JA-2, validation period.

5.4. Model validation and dam effectiveness

The model validation period was selected from January 1, 1995 to December 31, 2002. All the parameters were kept unchanged for the validation period. Only the recharge and well abstraction data were incorporated in the model for the specified period. The stress periods were also adjusted as per the validation period's wadi flow. The simulated heads from validation model were also close to the measured head. Figure 8 (a and b) presents a comparison between observed and computed values between 1995 and 2002.

The numerical simulations indicated that the annual recharge was about 1,825,000 m^3 prior to the construction of the Wadi Al Jizzi dam (period between Jan 1985 and Aug 1989). After the construction of the dam (period between Sep 1989 and Dec 1994) the annual recharge is estimated at 2,492,000 m^3. It is therefore concluded that the dam has increased the annual recharge in Wadi Al-Jizzi by about 36%. This can be clearly seen in the rise of groundwater levels after any flood event especially in the wells downstream of the dam. Nevertheless, over pumping along with the scarcity of rainfall has caused a drop in the groundwater levels in the last two years.

Therefore, Wadi Al-Jizzi dam has an efficient role in recharging the aquifers and increasing the groundwater levels. The tremendous increase in the groundwater pumping over the last few years has offset the positive impacts of the dam.

6. Conclusions

MODFLOW has been employed to simulate the groundwater conditions in the area of Wadi Al-Jizzi and assess the effectiveness of the dam. The model was conceptualized with single layer representing the alluvial aquifer. Recharge components included the surface runoff from the upper catchemnt. The through flow from the upper catchment has been considered by constructing a general head boundary. The model parameters have been calibrated until a satisfactory match between observed and simulated groundwater levels in most of the observation wells has been achieved for the period 1985 – 1994. The model was then validated, without changing the calibrated parameters, for the period 1995 to 2002.

Groundwater resources in the area of Wadi Al-Jazzi are generally overexploited leading to a considerable decline in groundwater levels. A remarkable decline in the groundwater level was observed in 2003. This was also associated with a deterioration of the groundwater quality especially near the coast. Groundwater levels fluctuate from one year to another based on the intensity of rainfall. The system recovers in the wet years. The effect of Wadi Al-Jizzi recharge dam is quite significant in the wells located just downstream of the dam. Based on the results of the numerical simulation, the dam has increased the annual groundwater recharge by 36% as compared to the conditions prior to the construction of the dam.

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GIS – Based hydrogeological and geophysical studies for groundwater exploration in the wadi tawiyean area, UAE

Salim Akram, Ahmed Al Mahmoudi,
Abdelazim Ebraheem and Ampar Shetty

GIS-BASED HYDROGEOLOGICAL AND GEOPHYSICAL STUDIES FOR GROUNDWATER EXPLORATION IN THE WADI TAWIYEAN AREA, UAE

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ABSTRACT

Reliability and validity of groundwater assessment and development strongly depend on the availability of large volumes of high-quality data. Putting all data into a coherent and logical structure supported by the computational environment helps ensure validity and availability of such data and provide a powerful tool for hydrogeological studies. To fill up the gaps in available hydrogeological data, vertical electrical resistivity sounding and 2D earth resistivity surveys were conducted during years 2003 and 2004 in Wadi Tawiyean. The drilling information of the newly-drilled and the existing pumping and observation wells was used to constrain the interpretation of the obtained geophysical data. Then a hydrogeological geographic information system (GIS) database was built to facilitate (1) groundwater–vulnerability analysis, (2) assessment of the impact of the constructed dam on groundwater recharge, (3) determination of the hydrogeological setting of the aquifer and (4) groundwater flow modeling which is crucially needed for predicting the impact of different groundwater management options.

Keywords: Wadi Tawiyean, artificial recharge, GIS applications in hydrogeology

1. Introduction

Rainfall forms the main source for recharging groundwater aquifer systems in the United Arab Emirates. Phreatic aquifers are recharged directly through rainwater infiltration, while confined aquifers are recharged through their outcropping areas. Apart from the quantity of rainfall, its distribution in space and time plays a vital role in the planning and management of water resources. When rain falls with heavy intensities and short durations, surface water runoff will be generated. The infiltration rate of the upper soil layer may not allow large quantities of the accumulated rainwater to percolate down through the soil and reach the aquifers. If the topography is flat, rainwater would continue to accumulate on the ground surface causing ponds in the depression areas. Otherwise, if the land surface is mountainous, the rainfall will be collected through a number of tributaries and would reach the course of the main wadi causing floods.

Wadi Tawiyean is located in the Emirate of Fujeira between latitudes 25 30 and 25 45 and Longitudes 56 00 and 56 13 (Fig. 1). It arises in the Jibal Ruus Mountains and flows to the west to the coastal plain. The catchment of Wadi Tawiyean consists of an extensive network of valleys comprising a surface area of about 195 km^2. The drainage net of Wadi Tawiyean is external, well developed, and mostly controlled by geologic structures. The maximum elevation is 1527 m above the mean sea level. The minimum elevation near the outlet at Burayrat is 108 m above the mean sea level. The flow characteristics in Wadi Tawiyean have only been monitored since 1991. Previous investigations indicated that the wadi has a mean annual flow and groundwater recharge of 1.96 x 10^6 m^3 and 9.04 x 10^6 m^3 respectively.

The sediments in Wadi Tawiyean are ranging in size from silt to boulder, and are derived from the rocks within the catchments area with an average thickness of 30 m. This layer is dry and characterized by low permeability ranging from 1 x 10^{-5} to 5.5 x10^{-6} ms^{-1}, underlain by dry cemented chert gravel, which in turn is underlain by saturated chert gravel in a silty matrix (Halcrow, 1994). These unconsolidated alluviums overlie an occasionally weathered/ fractured karistic limestone.

Due to the recharge-discharge imbalance, a distinctive depletion of the groundwater table has occurred in most of the shallow groundwater aquifers in UAE. Evolved from its prime role to develop the water resources in the country, the Ministry of Agriculture and Fisheries (MAF) has constructed a large number of detention and retention dams across the main Wadis. Wadi Tawiyean dam is an example of these dams. The main objectives of the present study are:

1. using the geophysical and hydrogeological methods to explore and evaluate the available groundwater aquifers in Wadi Tawiyean area,
2. determining the impact of the constructed dam on the rate of groundwater recharge from the rainfall water, and
3. evaluating the possible means of enhancing groundwater recharge under the present hydrogeological setting and infrastructure.

2. Geological and Hydrogeological Setting

The geological map sketch shown in Figure 2 indicates that Wadi Tawiyean is lying on the western side of the northern Oman Mountains, which are comprised of the Jurassic to Cretaceous Musandam Group limestone.

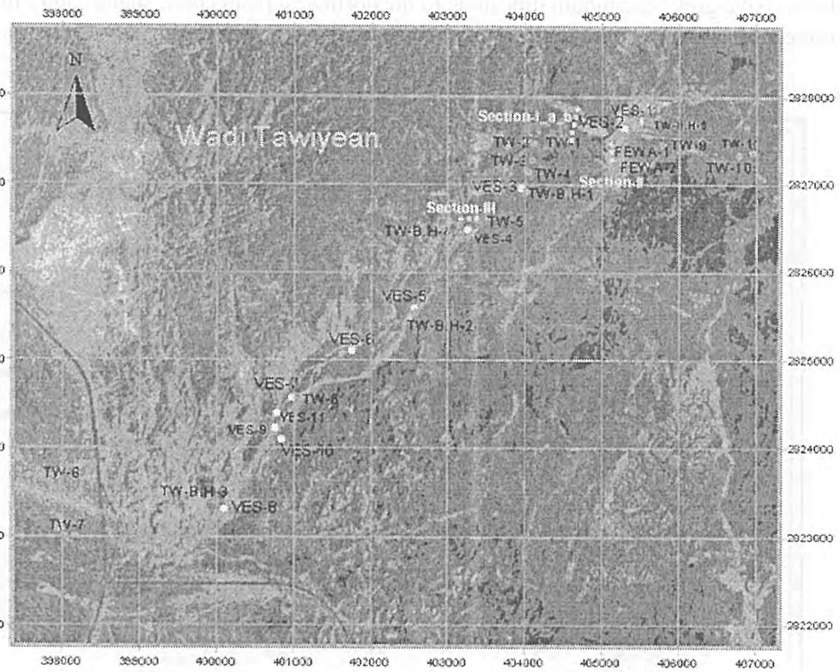

Figure 1: A satellite image for the catchment area of Wadi Tawiyean. The location of monitoring wells and geophysical cross sections are also shown

These mountains rise above the western Jiri coastal plain, which consists of late Teritiary to Recent alluvial sediments overlying the late Cretaceous Juweiza Formation. The Juweiza is a flysch-like sequence of marls and shale with varying admixtures of coarse detrital debris of cherts, basic igneous rock, and limestone. Southeast of the Musandam limestone lies the complex Dibba thrust zone with rocks of the Hawasina Complex and Aruma Group exposed along the southeast side of Wadi Tawiyean (Figure 2).

The area has been subjected to two major tectonic events. They are the thrusting of the Hawasina Formations and the Semail Ophiolite over the Musanadam limestone in the Upper Cretaceous and then the formation of the Oman Mountains due to folding, faulting, and thrusting in the mid Tertiary. This resulted in the formation of the major northeast-trending anticline structure through the Musandam Mountains, the Hagab thrust fault along the western edge of the mountains and the Jiri Plain and the Dibba Zone to the southwest with the Batha Mahani thrust running along the valley of Wadi Tawiyean and separating the massive grey Musandam limestone to the northwest from chert, shales, and limestone of the Hawsina Group to the southeast (Robertson et al., 1990).

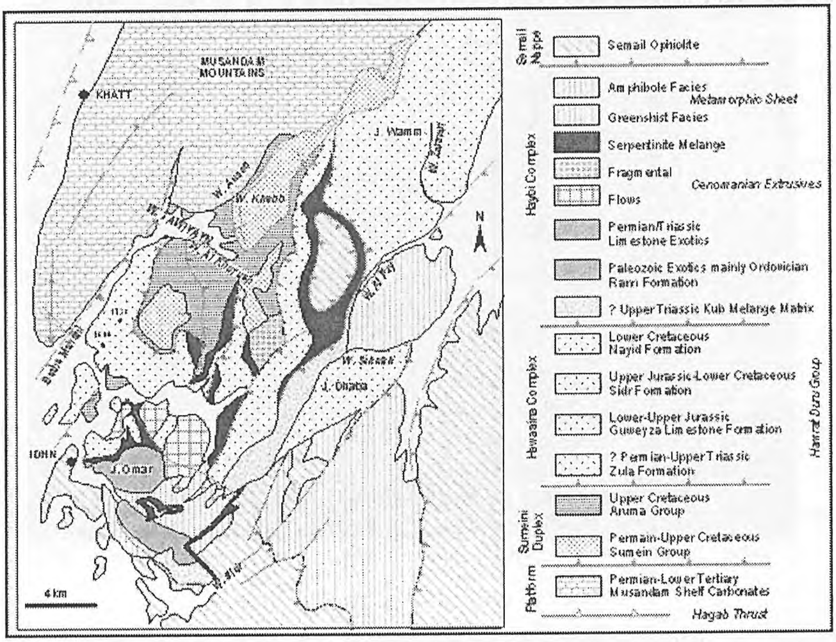

Figure 2: **Figure 5. Geological map of Wadi Tawiyean (after Entec, 1998)**

A geological map of Wadi Tawiyean (revised after Entec, 1998).

The lower plains of Wadi Tawiyean are derived from the decomposition of the Hajar carbonate sequences and Hawasina formations. The wadi gravels are comprised of material from silt to boulder size. Wadi gravels are composed of limestone gravels, chert gravels with clay silt matrix. Limestone gravels of the wadi bed are recorded to be generally rounded and of fine to coarse size, usually within a sand matrix. The degree of consolidation within the wadi gravels ranges from unconsolidated material at the surface to well cemented gravel horizons at depth. The top most layer of the Quaternary alluvium principally consists of Recent to Pleistocene wadi gravels. The consolidated alluvium overlies either karstic limestone or weathered/fractured Hawasina shale formation depending on the structural setting and location (Fig. 3).

The weathered zone of either limestone or shale is observed between gravel with boulder and rock-bed. The maximum thickness of the layer is observed in the area of well number T-BH-1 and a minimum at the well number T-BH-5. The depth to limestone rock bed varies from 46 to 77 m. The lithological cross-section along the wadi course (Fig. 3) indicates that wadi gravels, transition zone and depth of bed rock vary with respect to the locations. TW-1, TW-4, TW-5, and TW-6 are located in the zone of Hawasina formation, whereas wells T-BH-3 and T-BH-5 are located in the zone of Musandam formations.

Based on the drilling information, interpretation of geoelectric sections, and the water table configuration, two aquifers can be identified, namely the upper aquifer which consists of wadi gravels and the lower aquifer which is consisting of weathered limestone or shale.

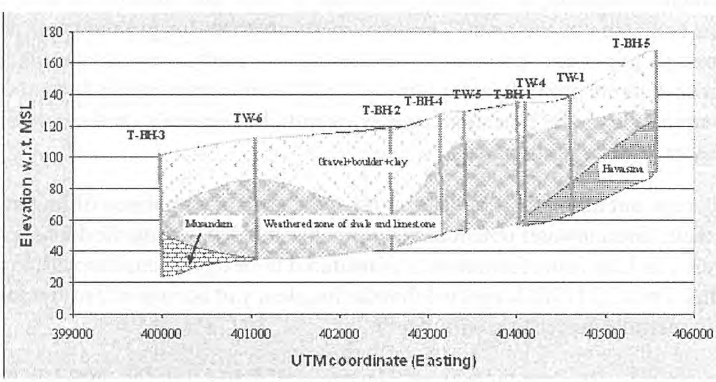

Figure 3: Lithological cross-section along selected boreholes (Modified from ENTEC, 1998). For borehole locations see Fig.1.

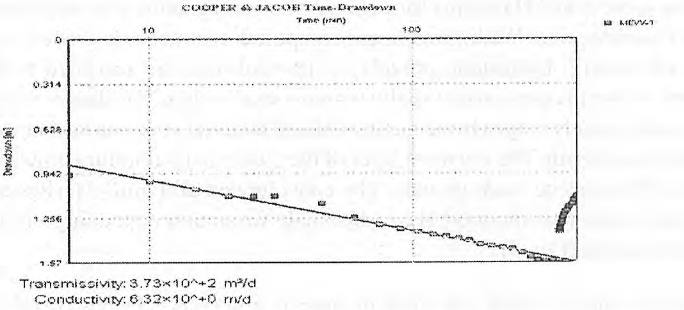

Figure 4: Fitting Cooper–Jacob (1946) straight line approximation of Theis (FEWA-1)

The wadi superficial gravels are highly permeable and have varying hydraulic properties due to the variations in the degree of consolidation with depth. The estimated permeability of limestone gravels of the wadi is in the range of 0.05-0.9 m/d (Halcrow, 1994). Wadi gravels towards the west and mouth of the wadi were observed to be more matured and better sorted and thus having higher permeability. In the places where the gravels start to become slightly cemented, fissures might occur and these could be important for groundwater exploration.

The Musandam limestone is typically grey, fine grained and massive to thickly bedded towards the right side of the wadi. The primary mechanism for groundwater storage and flow is through joints and fissures of weathering or kastification. Generally, karstified aquifers have discrete groundwater pathways and variable interconnections and very low primary permeability. The limestone aquifer potentiality depends on the enhancement of joints, fissures, and bedding planes.

Hawasina crops out along the left bank of the wadi ansd is comprised of metamorphosed chert and shale. Groundwater potentiality within this unit depends on the degree of fractures and fissures. The Hawasina formation is considered to be a poor aquifer with low primary permeability. IWACO (1986) reported that the frequency of occurrence of fractures within the unit is generally decreasing with depth.

Two pumping tests were conducted very close to well T-BH-5 in July 2003 by the Federal Electricity and Water Authority (FEWA) for a duration of 360 minutes. The drawdown curves were analyzed. An example of the interpreted pumping test data is shown in Figure 4.

3. Geophysical Investigations

Surface geophysical methods are regarded as rapid, inexpensive methods for determining the locations and orientation of fractured zones in bedrock. Surface geophysics can be used in conjunction with geologic, hydrologic, and borehole-geophysical investigations to optimize well sitting (Jansen and Jurcek, 1997). In some cases, surface geophysics can be used as a stand-alone method of fracture detection (Lewis and Haeni, 1987; Haeni and others, 1991, Haeni and others, 1993).Vertical Electrical Sounding (VES) and 2D Earth

Resistivity Imaging Tomography methods were used to determine the locations of the fracture zones in the limestone bedrock of Wadi Tawiyean.

Vertical electrical soundings were collected near the existing borehole for which drilling information is available to constrain the interpretation of the VES data and obtain a true resistivity range for each lithologic layer. The 2D resistivity profiles were constructed along the strike direction to intersect the maximum possible number of geologic features and lineaments. Three 2D profiles and eleven VES were collected from different sites in the main channel of Wadi Tawiyean (Fig. 1).

3.1. Geophysical Data Processing & Interpretation

In Wadi Tawiyean, three 2D dc-resistivity profiles were collected (near the dam, FEWA production well, and TW-4 observation well). For each line, the Wenner array was used. The apparent resistivity data were inverted to create a model of the resistivity of the subsurface using Res2dinv. Res2dinv uses an iterative smoothness-constrained least-squares method (deGroot-Hedlin and Constable, 1990; Sasaki, 1992).

To test interpretation, resistivity models were created based on the inversion results. The resistivity models were used to generate synthetic apparent resistivity data. The synthetic apparent resistivity data were inverted using Res2dinv program (Loke, 1997) and the resulting inversions were compared with the original inverted resistivity section. The resistivity models were adjusted and simplified to qualitatively match the field-data inversions. Generating resistivity models helped constrain interpretation of the field-data inversions to identify locations and orientations of anomalies.

The known NE-SW fault line separating between the shale layer (Gweiza formation) which has a resistivity of less than 50 Ohm m from the limestone (Hawasina formation) is detected in Profiles 1 and 2. The dry limestone has a resistivity range of 1000-500 ohm meters while saturated fractured limestone has a resistivity range of 50-150 Ohm meters. The interpretation results of Profile 2 traversing across the FEWA production well indicates that this well is located in a zone where the limestone is highly fractured (Fig. 5).

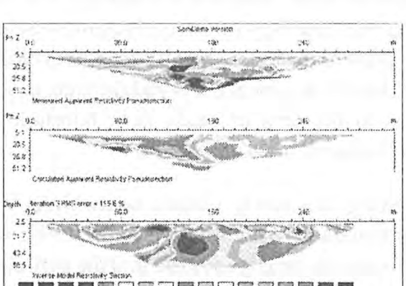

Figure 5: An example of observed and synthesized resistivity data together with the inverted true resistivity-depth section (Profile 2), Wadi Tawiyean. See Fig. 1 for the profile's location.

Eleven vertical electrical soundings (VES) using Schlumberger electrode configuration with a maximum current electrode spacing "AB" = 800m have been carried out in Wadi Tawiyean (Fig. 1). The topography in terms of the access to extend the wire for 800 meters without any considerable change in the elevation along the profile which is always taken parallel to the stike of the limestone layer has controlled the number and location of the conducted VES stations. The Sting R IP geoelectric DC-equipment has been used for the data acquisitions. The geoelectrical field data were presented in the form of resistivity sounding curves. Such curves represent the relation between the measured apparent resistivity (ra) and half the current electrode spacing"AB/2" on log-log scale.

The sounding data analysis was carried out using two modern techniques which proved the equivalent layering. These techniques are: the fully automatic data inversion which is mainly based on the n-layers step function model suggested by Zohdy and Bisdorf (1989) and the forward modeling technique in which the interpretation of the sounding curve is carried out through a user-interaction process as follows:

1. An approximate model for the sounding curve was manually suggested taking into consideration any useful information about the subsurface, either from existing wells; from nearby wells or from previous geological or geophysical reports about Wadi Tawiyean.

2. The proposed model was then subjected to successive iterations till a calculated curve is reached having a good fit with the observed data with the least root mean square error.

3. The calculated parameters (depth, thickness and true resistivity) were then picked up from the best fit curve to represent the subsurface layering.

4. The interpreted curves for all VES were then correlated with each other as well as to the available drilling information to find the characteristics of the area regarding the rock lithology and hydrogeological conditions.

The geophysical model parameters of interpreted sounding curves are summarized in Table 1. Since the electric resistivity of rocks depends with different degrees on many factors such as porosity, groundwater, ionic content and lithology, there are no general applicable guidelines for interpreting the lithology of the contrasting resistivity layers, as each area has its own conditions (non uniqueness problem). Therefore, the interpretation of geoelectrical data must be based on a local basis and include, any independent information about the nature of rocks in the area of study (e.g. borehole data, hydrological data, geological and structural features).

Borehole data of the existing and newly drilled water wells was used to constrain the interpretation of the sounding data. The correlation of the VES data interpretation results with the borehole's information obviously indicate that the surficial layers which are mainly dry boulder attains high resistivity and extends from the surface to a minimum depth of 2.5 m. In addition to the drilling information, the water table information during the time of taking these measurements was used to divide the Quaternary alluvium into two zones: the first one represents the high resistive unsaturated zone and the second represents the low to moderate resistive saturated zone. The dry massive limestone has the highest resistivity values and the fractured limestone has moderate resistivity values. Hawasina shale has the lowest resistivity values as shown in the geoelectric cross section (Fig. 6).

Table 1: Qualitative and quantitative interpretation of the Vertical Electrical Sounding curves measured for 11 sounding points in Wadi Tawiyean

			True resistivity (Ohm-m)					Depth to Layer Base (m)				
VES	Curve No	No of Type	r? Layers	r_2	r_3	r_4	r_5	D1	D2	D3	D4	D5
1HK	4	9,435	1,594	4,616	35		0.51	1.82	31.22			
2K	3	984	9,613	136			0.62	8.52				
3QH	4	42,789	4,988	140	391		2.25	21.95	95.87			
4QQH	5	5,121	1,417	922	117	3412	0.52	2.04	34.13	101.84	167	
5KH	4	113	4,767	17	1,965		0.58	3.41	25.34			
6K	3	344	44,963	158			0.46	4.88				
7HK	4	246	85	1390	116		0.47	4.38	68.6			
8K	3	59	1,430	44			0.52	15.5				
9H	3	25,003	761	139,580			0.54	1.74				
10	QQ	4	61,524	2,899	190	34		1.01	4.08	60.07		
11	K	3	760	19,473	42			0.9	6.6			

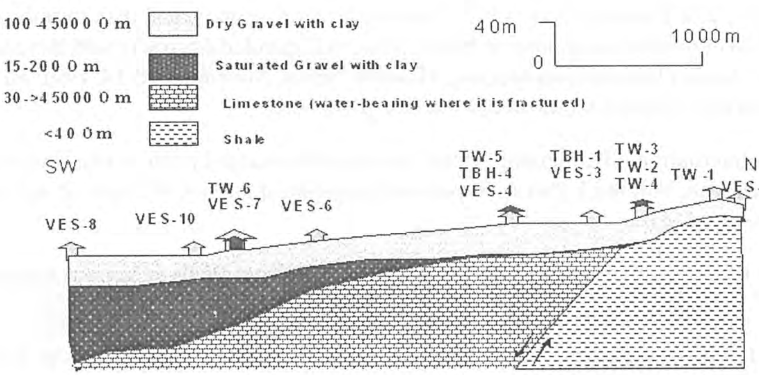

Figure 6: Geoelectric subsurface cross section along the SW-NE direction

4. Conclusions

The inverted resistivity data together with the available drilling information and water table data of the old and newly-drilled wells indicate the presence of two aquifers in the area of Wadi Tawiyean, the Quaternary (or shallow) aquifer and the fractured limestone (or deep) aquifer. The Quaternary aquifer is regarded as the main aquifer and is composed of the unconsolidated sediments (mainly alluvium gravel and coarse sand).

The Quaternary aquifer is directly recharged from the percolating rainfall. Historical groundwater measurements indicate a significant variation in the response to recharge events and groundwater abstractions from one area to the other mainly depending on its distance from the dam. This indicates that the constructed dam has been playing a major role in enhancing the recharging rates of the shallow aquifer.

The Quaternary aquifer is well studied and currently is exploited for domestic and agricultural purposes. On the other hand, the bedrock aquifer was not tested and needs further detailed study. However, the results of the 2D earth resistivity imaging survey indicate that this bedrock aquifer is probably extending for several hundreds of meters and thus constitutes a deep groundwater aquifer with high groundwater potentiality in the areas where it is strongly fractured and karistified.

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Ground – surface deformation over Al Ain and Surround Area, United Arab Emirates, measured by interferometric synthetic aperure radar (INSAR)

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GROUND-SURFACE DEFORMATION OVER AL AIN AND SURROUNDING AREA, UNITED ARAB EMIRATES, MEASURED BY INTERFEROMETRIC SYNTHETIC APERTURE RADAR (INSAR)

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ABSTRACT

In arid areas, subsidence has been observed where there have been large groundwater withdrawals. The opposite of subsidence, known as uplift, may be occurring because of local neo-tectonism or abnormal groundwater recharge. Quantifying this deformation has traditionally been accomplished using spirit leveling and, more recently, Global-Positioning-System surveys. Also recently, a new tool, Interferometric Synthetic Aperture Radar (InSAR), has been used that has dramatically improved the capability to map ground-surface deformation. In InSAR, repeat-pass radar images from Earth-orbiting satellites are utilized to measure land deformation at centimeter (cm) to millimeter (mm) levels at spatial scales or tens of meters. Utilizing interference phenomena between radar waves, InSAR measures the corresponding phase difference between two radar waves resulting from differences in the round-trip path length to the same ground point between two satellites passes. Phase difference arises from many reasons, but that arising from ground deformation is of prime interest. Representation of the interferometric data is done by assigning different colors to portions of a wavelength cycle. Each color cycle change represents a certain amount of deformation. From the color-change trend-sequence cycle, subsidence or uplift can be quantified. Interpretation of InSAR data indicates that subsidence is extensive in the Al Ain area. The InSAR derived rate of subsidence during the 1996-99 periods (7 to 8 mm/year) is larger than the 1992-96 periods (0 to 3 mm/year). The increase in subsidence may be attributed to an increase in groundwater withdrawals. In general, subsidence rates throughout Al Ain area varied from 0 to 1.9 cm per year (1992-99). Uplift is also suspected northeast of Al Ain, probably related to neo-tectonic activity, but the amount of uplift was not quantified in this study. InSAR may also contribute to geologic investigations and determining the hydrogeology of the entire aquifer-system underlying Al Ain and vicinity.

Key words: subsidence, InSAR, Al Ain, deformation, neo-tectonic.

Introduction

An aquifer system is a saturated, heterogeneous body of interbedded permeable and poorly permeable hydrogeologic units, called aquifers and confining units, respectively. In unconsolidated or semi-consolidated deposits, the aquifers and confining units are linked hydrologically. When groundwater levels decline, often as a result of increased groundwater pumping, support for the overlying material may shift from the pressurized pore fluid to the granular skeleton of the aquifer system, and the land surface subsides. Conversely, when ground water is recharged and groundwater levels rise, some support for the overlying material shifts from the granular skeleton to the pressurized pore fluid, the skeleton expands and the surface inflates [Galloway et al., 1999]. When ground-water levels decline sufficiently so that stress on the confining units becomes greater than the maximum previous stress (preconsolidation stress), the confining units compact and the land surface subsides0 causing permanent loss of aquifer storage. Most permanent subsidence occurs because of irreversible (inelastic) compression or consolidation of confining units. However, recoverable (elastic) subsidence can occur in both aquifers and confining units [Galloway et al., 1999].

Interferometric (In) Synthetic Aperture Radar (SAR), (InSAR) utilizes two or more coherent phase signals acquired at different times for the same land area to map changes in range (satellite-to-earth distance) with a spatial resolution of tens of meters and a vertical accuracy of centimeters [Massonnet and Feigl, 1998]. InSAR analysis of an aquifer system involves mapping and analyzing the surface deformation caused by hydrogeologic processes [Amelung et al., 1998; Galloway et al., 1999; Massonnet et al., 1997; Lu and Danskin, 2001]. InSAR measures the corresponding phase difference between two radar waves resulting from differences in the round trip path length to the same ground point between two satellite passes. Phase difference may result because of five possible effects: (1) differences in the satellite orbits of the two passes, (2) topography, (3) ground deformation, (4) atmospheric propagation delays and, (5) systematic and environmental noises. By removing the effects caused by different satellite orbits, and topographic effects (an accurate digital elevation model (DEM) is required), the component of land deformation along the satellite's look direction potentially can be measured with a precision of 1-2 cm or better. This technique is often referred to as "2-pass" interferometry [Massonnet and Feigl, 1998]. Because problematic atmospheric propagation delays remain in the data, repeat observations are needed to confidently interpret the small geophysical signals related to land-surface deformation. To derive useful information from an interferogram, the SAR returns also must be coherent between image acquisitions. Interferometric coherence is a measure of the variance of the phase signal in an interferogram [Lu and Freymueller, 1998]. Thus, the degree of coherent interference between two SAR images is dependent on the changes associated with the scattering characteristics of the ground surface between the two radar acquisitions. Therefore, the coherence of an interferogram will be highest when the scattering characteristics of the illuminated surface remain unmodified, whereas a loss of coherence may be caused by the random movement of scattering objects (sand dunes), or by other factors, such as changes in surface vegetation. No meaningful deformation information can be extracted over areas with complete loss of interferometric coherence.

The purpose of this paper is to present the results of our study on measuring the ground-surface deformation measured by InSAR in and around Al Ain, United Arab Emirates (UAE).

Study Area

Al Ain is located in the northeastern part of the United Arab Emirate (UAE), a rapidly developing country in the Arabian Peninsula (Figure 1) [Al Sharhan et al., 2001]. The rapid growth has escalated agricultural, domestic, and industrial demands for groundwater, which is the only natural source of fresh, moderately brackish and brackish water in the UAE. In 1995 the Al Ain aquifer contained approximately 4 cubic kilometers (km^3) of fresh water, representing approximately 20 percent of the total amount of water available to the UAE [Silva et al., 2003]. Most of Al Ain's fresh and brackish water is stored in a surficial aquifer that is seldom more then 100 meters (m) thick [Silva et al., 2003]. The surficial aquifer underlying Al Ain consists of recent aeolian sands, Quaternary alluvium (interbedded cemented gravels, silt, and sands), Miocene clastics (Marls, clays sands and siltstones), and carbonate sediments. The surficial aquifer generally is unconfined and groundwater flows east to west from the aquifers recharge area in the Oman Mountains [Al Sharhan et al., 2001; Silva et al., 2003]. Limited natural recharge of the surficial aquifer and over-pumpage are depleting groundwater sources at an increasing rate, resulting in sizable depression cones near Al Ain and other areas in eastern UAE over the past 30 years [United Arab Emirates University, 1993; Al Sharhan et al., 2001].

InSAR Observations

To study land-surface deformation in the Al Ain area, InSAR techniques were used with imagery acquired by the C-band SARs (wavelength = 5.66 cm) onboard the European Space Agency (ESA) ERS-1 and ERS-2 satellites. The ERS-1 and ERS-2 images collectively span September 30, 1992 to September 7, 1999 (Table 1). The 2-pass InSAR method [Massonnet and Feigl, 1998] was used to produce the land-surface deformation map. The digital elevation model (DEM) from Shuttle Radar Topography Mission (SRTM), acquired in February 2000, was used in this study. The 3-arc-second (about 30 m) SRTM DEM has a relative vertical accuracy better than 10 m and an absolute vertical accuracy better than 16 m [Farr and Kobrick, 2000; NIMA Fact Sheet at http://164.214.2.59:80/srtm/factsheet.html].

Fifteen interferograms were produced for this study. The interferometric baseline – the spatial distance between repeat satellite passes - ranges from 24 to 229 m (Table 1). The relatively short baselines indicate that the interferograms will be relatively insensitive to errors in the DEM [Massonnet and Feigl, 1998]. Interferometric coherence is well maintained over urban and alluvium areas that are not densely vegetated, but coherence is lost over sand dunes, agriculture fields and more densely vegetated areas.

Three interferograms (Table 1) were selected to be representative of the deformation observed in all 15 interferograms. These three interferograms were chosen because they covered the maximum amount of time while maintaining a high degree of coherence. However, the 13 interferometric pairs not included in this study confirm that the deformation observed in the three representative interferograms is true deformation and is not the result of atmospheric contamination. The first two interferograms (Fig. 2 and 3) respectively, span the time periods between November 4, 1992 to May 10, 1996 and May 10, 1996 to June 5, 1999 (Table 1). The third interferogram (Fig. 4), with a time separation of 2,402 days, collectively spans the time interval of the first two interferograms. The look angle of the ERS satellites is about 23 degrees from vertical, so the interferogram is sensitive mostly to vertical ground movements. Each fringe (a full color cycle) in the interferogram represents 1.4 cm of deformation along the satellite line-of-sight, which corresponds to 1.5 cm of vertical deformation.

Table 1: SAR images used for this studying Al Ain and surrounding area, UAE. Dates are image acquisition times in yyyymmdd format. Orbit numbers include the satellite ID (E1 = ERS1, E2 = ERS2) and orbit on which the images were acquired. The same track number applies to both images in an interferometric pair. Bn is the baseline length (the perpendicular component). — or NA indicates not applicable.

Orbit 1	Date 1	Orbit 2	Date 2	Time separation (days)	Bn (m)	Figure
E106821	19921104	E125201	19960510	1283	60	Fig. 2
E125201	19960510	E221560	19990605	1121	9	Fig. 3
E106821	19921104	E221560	19990605	2404	69	Fig. 4
E106320	19920930	E107823	19930113	105	171	--
E106320	19920930	E205528	19960511	1319	187	--
E106821	19921104	E205528	19960511	1284	229	--
E107322	19921209	E205027	19960406	1214	45	--
E107594	19921228	E125473	19960529	1248	24	--
E107594	19921228	E205800	19960530	1249	136	--
E108324	19930217	E125201	19960510	1178	198	--
E108324	19930217	E205528	19960511	1179	129	--
E108324	19930217	E221560	19990605	2299	189	--
E132566	19971006	E222913	19990907	701	41	--
E205528	19960511	E221560	19990605	1120	160	--
E125201	19960510	E205528	19960511	1	169	--

Land-surface deformation occurring between November 4, 1992 and May 10, 1996 is shown in Figure 2. The progression of colors from red, to yellow, to blue indicates that the ground target moved away from the satellite vantage point (mostly down). Uncolored pixels represent areas where meaningful deformation measurements were not possible because of loss of interferometric coherence. Complex deformation patterns are indicated from Figure 2. Deformation sections along eight profiles are used to further analyze the interferogram (Figure 5). Over the Al Ain International Airport, (at end near point A'; see Fig. 5a) about 15 millimeters per year (mm/year) of subsidence with respect to point A (Fig. 5a) occurred during the 3.5-year period. Deformation along the profile B-B' indicates that B' subsided at a rate of about 4 mm/year with respect to point B (Fig. 5b). Similarly, deformation along the profile G-G' indicates that G' subsided about 19 mm/year with respect to G (Fig. 5g). The deformation pattern between points G and A' indicates that A' subsided with respect to G (Fig. 3). By synthesizing the observed deformations along these profiles, the approximate locus of subsidence is probably to the east of well 064.

Not every part of the study area subsided during the time window of the Interferogram (Fig. 2). For example, the ground near well 021, was uplifted about 5 mm/year with respect to the surrounding area (for example, well 066) (Fig. 5h) as indicated by the H–H' profile. The deformation over this area probably is related to thrust fault activity (Fig. 6) [Woodward, 1994], as opposed to uplift resulting from ground-water recharge [Lu and Danskin, 2001].

The Interferogram shown in Figure 3 indicates the land-surface deformation between May 10, 1996 and June 5, 1999. The deformation pattern observed in the 1996-99 Interferogram is similar to the pattern observed in the 1992-96 Interferogram (Fig. 2). The rate of deformation during 1996-99 is, in general, larger than that observed during the 1992-96 period. For example, the subsidence rate along the profile B-B' increased from -3 mm/year during 1992-96 to about -7 mm/year during 1996-99 (Fig. 3a), where-as the subsidence rate along the profile C-C' increased from nearly 0 mm/year to -8 mm/year (Fig. 5c). However, subsidence along the profile G-G' changed from -19 mm/year during 1992-96 to -10 mm/year during 1996 to 99 (Fig. 3e). It is interesting to note that the deformation rate along the profile H-H' is consistent with the rate observed during the previous observation period, including the previously mentioned area of uplift located near well 021.

The deformation from November 4, 1992 to June 5, 1999, (essentially the sum of observed deformations in Figures 2 and 3) is shown in Fig.2. Spanning 2,402 days, (Table 1) the fringes in the 1992-99 Interferogram are considerably denser than the fringes observed in Figures 2 and 3. The orientation of profiles A-A' and B-B' (Fig. 4) indicates that a depression cone is located near A' and B' to the east of well GWP-063. The orientation of the fringes to the north and east of point F' indicate a possible locus of depression south of the point, in the area of low coherence. However, a possible source for the deformation could not be determined because of the lack of coherent data.

Discussions and Conclusion

To understand the observed land-surface deformation (Figs. 2, 3, 4 and 5), changes in the ground water levels were monitored in eight wells in the study area from 1992 to 1999 (Table 2). Observed deformations over the area near the profiles A-A' and B-B' profiles indicate a locus of subsidence to the east of well GWP-064 (Fig. 1). Generally, ground-water levels are lower in 1999 than in 1992. The largest water-level decline (about 21m) resulted at well GWP-064.

The relative surface deformation between wells GWP-064 and GWP-065 indicates that the land-surface near well GWP-064, with respect to well GWP-065, subsided more than 20 mm from November 1992 and June 1999. This result is consistent with the water-level change between well GWP-064 and well GWP-065 as the water table drawdown at well 064 (20.9 m) is greater than the drawdown at well GWP-065 (6.5 m). Similarly, the observed subsidence of about 30 mm between wells GWP-063 and GWP-066 during 1992-99 is consistent with changes in water levels (Table 2). Therefore, the observed land-surface deformation over Al Ain and Al Saad is most likely induced by deformation of the aquifer system in response to changes in the water table that is attributed to changes in natural recharge and pumping [Silva et al., 2003].

The changes in groundwater level over the study area are spatially heterogeneous and vary with time. For example, even though the amount of water-table drawdown during 1992 and 1999 is greater in well GWP-064 than in well GWP-065, the majority of drawdown in well GWP-064 occurred between November 1992 and May 1996 whereas, the majority of drawdown in well GWP-065 occurred between May 1996 and June 1999. For (wells GWP-021, -061, -065 and -066) of the eight wells in the study area, the majority of water level changes occurred between May 1996 and June 1999. The drawdown rate for the wells (GWP-055 and 082) was relatively constant from November 1992 to June 1999. Water levels rose only in two wells (GWP-021 and GWP-055) during this period. This was most likely due to recharge (GWP-021) and the cessation of pumping (GWP-055). Therefore, given the current demand for fresh water, the recharge rate for most of these wells is insufficient to satisfy current withdrawals and, hence, water levels will continue to decline.

Table 2: Ground-water levels measured in eight wells in the InSAR study area 1992-99.

Well Number	**Water level (m above sea level)**			**Change in Water level (m)**		
	1992.11.04	**1996.05.10**	**1999.06.05**	**1996 minus 1992**	**1999 minus 1996**	**1999 minus 1992**
GWP-021	219.2	223.7	234.0	4.5	10.3	14.8
GWP-055	144.0	146.0	149.0	2	3	5
GWP-061	112.9	111.0	102.0	-1.9	-9	-10.9
GWP-063	141.5	134.2	123.0	-7.3	-11.2	-18.5
GWP-064	142.3	124.5	121.4	-17.8	-3.1	-20.9
GWP-065	197.0	196.7	190.5	-.3	-6.2	-6.5
GWP-066	253.0	251.8	245.0	-1.2	-6.8	-8
GWP-082	158.6	158.5	158.4	-.1	-.1	-.2

The estimated saturated thickness of the surficial aquifer underlying the UAE is based on water table maps and maps of aquifer base. The estimated saturated thickness generally is less than 100 m [Silva et al., 2003]. The interferograms may indicate that aquifer permeability is highly heterogeneous. From Al Saad to Al Ain, the observed complex pattern of surface deformation (Figs. 2, 3, and 4) indicates variable aquifer properties throughout the study area. This indication also is consistent with the difference in groundwater levels (Table 2).

Deformation in the area northeast of Al Ain (Fig. 4) probably is related to tectonic activity. This area is located on a structural transition between the uplifted, highly deformed rocks of the Oman Mountains to the east, and the buried, flat-lying strata to the west (Fig. 6). Numerous thrust faults, dipping nearly vertically to the east and trending to the northwest, have been identified [Woodward, 1994]. InSAR has been used to locate the location of faults that restrict ground-water flow, recharge areas, and determine the areal distribution of fine-grained aquifer materials [Lu and Danskin, 2001]. In this study, it has been shown that InSAR can be used to locate fault displacements (Fig. 6). This capability will contribute to the better understanding of the aquifer system underlying the Al Ain area [Silva et al., 2003; Woodward, 1994]. InSAR has been used successfully here in determining land-surface deformation at useful spatial resolutions.

Acknowledgements

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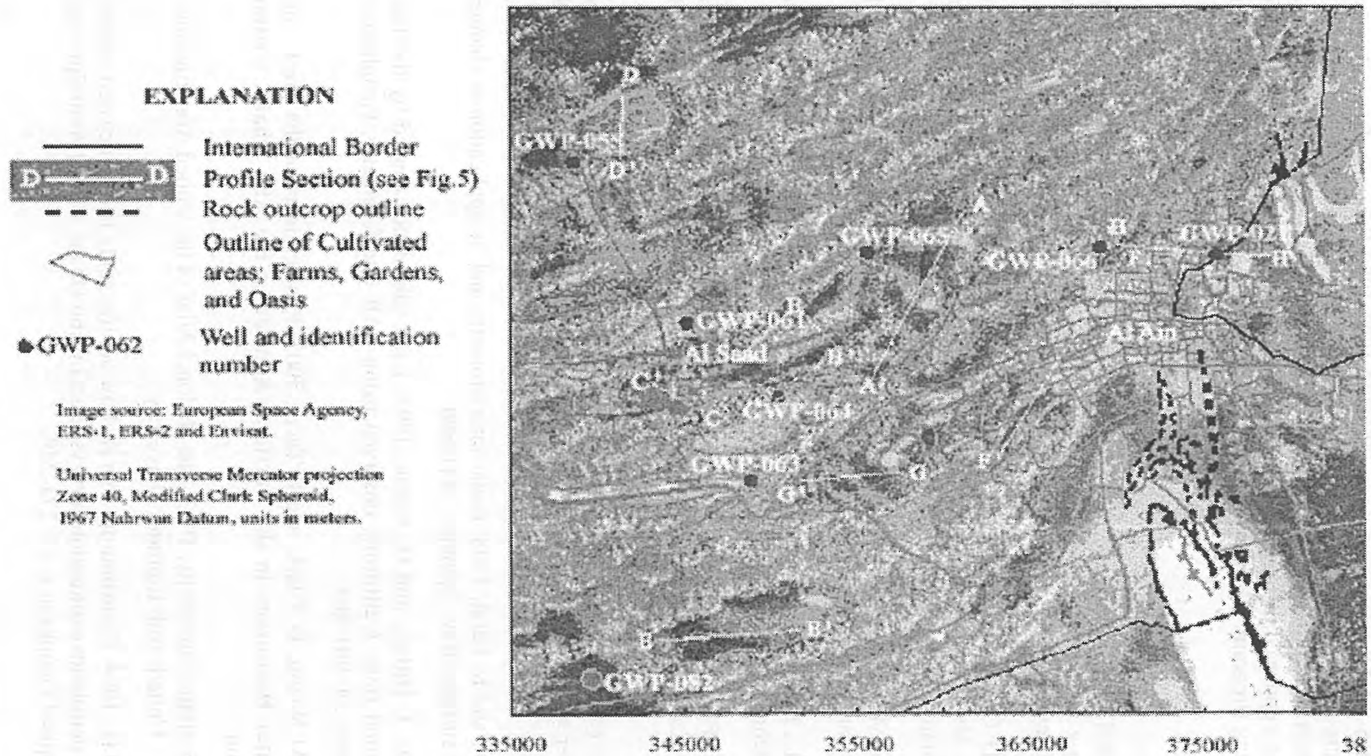

Figure 2: SAR interferogram of land-surface deformation in the Al Ain and Al Saad areas, UAE, during the period from November 4, 1992, Orbit E106821, to May 10, 1996, Orbit E125201. Each fringe (full color cycle) in the interferogram represents 1.4 cm of range change between the ground and the satellite, which translates to 1.5 cm of vertical deformation. Profile sections are approximate length (Fig.5).

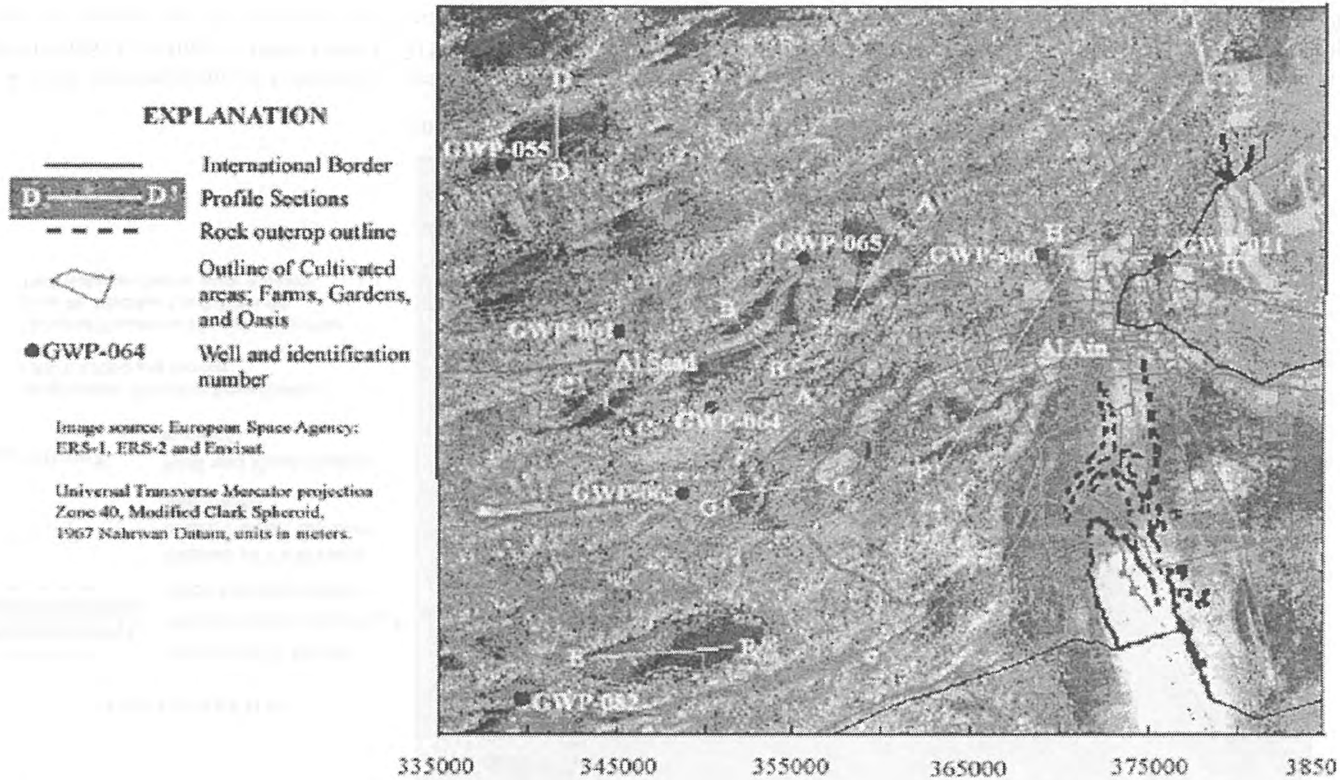

Figure 3: SAR interferogram of land-surface deformation in the Al Ain and Al Saad areas, UAE, during the period from May 10, 1996, Orbit E125201, to June 5, 1999, Orbit E221560. Each fringe (full color cycle) in the interferogram represents 1.4 cm of range change between the ground and the satellite, which translates to 1.5 cm of vertical deformation. Profile sections are approximate length (Fig. 5).

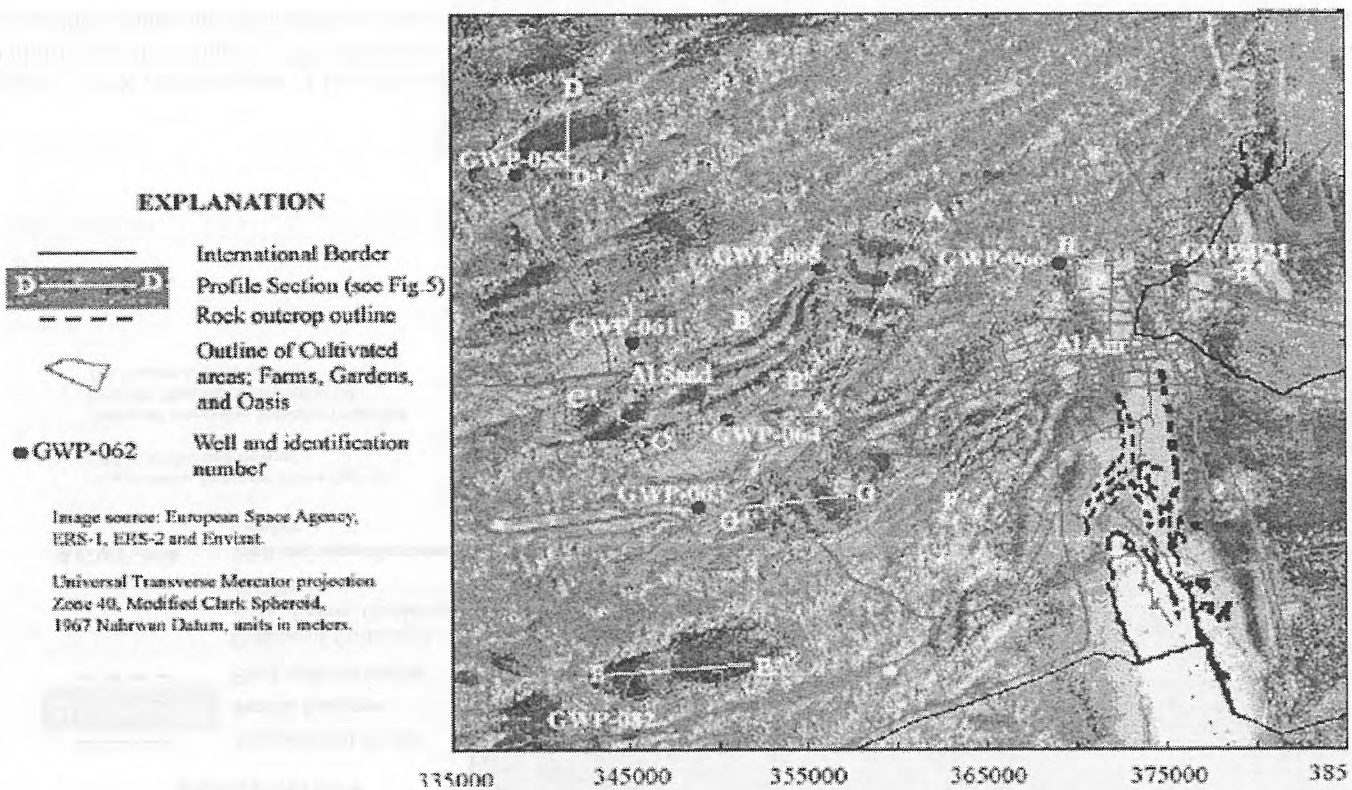

Figure 4: SAR interferogram of land-surface deformation in the Al Ain and Al Saad areas, UAE, during the period from November 4, 1992, Orbit E106821, to June 5, 1999, Orbit E221560. Each fringe (full color cycle) in the interferogram represents 1.4 cm of range change between the ground and the satellite, which translates to 1.5 cm of vertical deformation. Profile sections are approximate length (Fig.5).

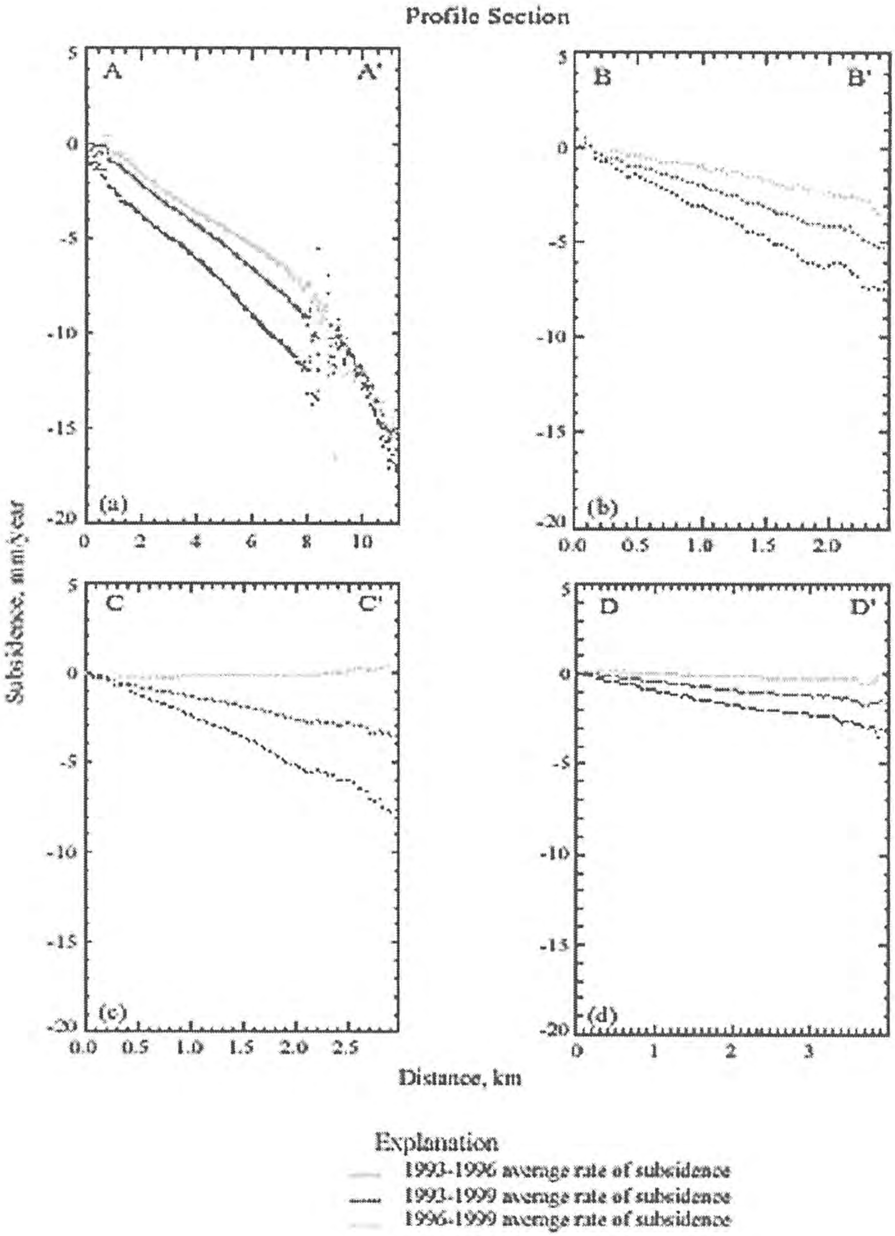

Figure 5: Rate of land-surface deformation determined by InSAR for the profiles found in Figures 2, 3 and 4 are shown.

A cost-effective method to map the top of shallow groudwater systems

Mohammad Makkawi and Abdullatif Al-Shuhail

A COST-EFFECTIVE METHOD TO MAP THE TOP OF SHALLOW GROUNDWATER SYSTEMS

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ABSTRACT

This paper presents an integrated GPR-OK procedure to detect the depth to a water table below the ground surface. The study evaluates the applicability of this approach to locate a water table using an inexpensive and efficient procedure. The proposed methodology may be utilized to map the surface of a shallow groundwater resource or detect the spatial extent of groundwater contamination. A pilot study was conducted in a small area of an interdune terrain in the Jaforah Desert system of Eastern Saudi Arabia to test the approach. The hydrogeologic data was acquired by a 300 MHz antenna of a SIR-2 GPR system. A velocity of 0.15 m/ns was used for time-to-depth conversion. Preliminary analysis indicates that the depth to water table lies in the range of 65 cm to 68 cm. The result indicates that this method may be employed in larger scale projects to assess new groundwater resources or monitor and manage the extent of groundwater pollution.

Keywords: Groundwater, Ordinary Kriging, Geostatistical model, GPR, Saudi Arabia.

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Introduction

The endeavor to explore groundwater resources, protect aquifer environment and construct civil structures, necessitates identifying the position of the underneath water table accurately. To generate dependable watertable maps, Depth to Ground Water (DGW) data is required. Usually these data are obtained by installing a considerable number of monitoring wells at different locations, particularly when dealing with branching alluvium aquifers and groundwater systems under urban or restricted areas. This is a difficult and expensive task that consumes a lot of time.

Several techniques were tested to detect shallow groundwater systems and aquifer boundaries. One of these exploration methods was the Ground Penetrating Radar (GPR). Utilization of GPR in detecting shallow groundwater systems is advantageous because of its high-resolution output, economic implementation, rapidity, and portability of field instruments. The GPR employs the concept of dielectric constant and electrical conductivity contrasts to differentiate hydrogeologic units like the top of a groundwater system from the vadose zone.

The objective of this paper is to map the surface of a shallow groundwater system by a cost-effective GPR-OK (Ordinary Kriging) method. The procedure used in this study aims at constructing a network of "imaginary monitoring wells" and observes the DGW in each "well". DGW observations will be used as control points to accurately map the surface of a shallow groundwater system using the OK procedure.

Study Area and Data Set

The study was conducted in a flat small area of the Jaforah Desert about 5 km SE of Abqaiq city, Eastern Saudi Arabia (Fig. 1). Several water ponds were observed in the area that intersect a shallow groundwater system. The system is most probably associated to the buried "Abqaiq River" (Weijermars, 1999). A small pond of about 12 x 7 x 1 m dimensions is located 8 m to the E-SE of the study area. Water level in the pond was about 70 cm below ground surface. A water sample was analyzed in the field and indicated a brackish water quality with a TDS value of 5500 mg/l.

A 300-MHz GPR antenna was used to acquire DGW data. Figure 2 shows the locations of the "imaginary monitoring wells" that are distributed on a regular grid network of 1.5 x 1.5 m. In each trace or ""well", a two-way travel time was measured. Based on a field experiment, the velocity value of 0.15 m/ns was used for time-to-depth conversion. DGW values were calculated for each trace and used to map the surface of the existing shallow groundwater system.

Methodology

The DGW data set was analyzed using statistical methods to show population characteristics (Davis 2002). A probability plot was constructed to identify data normality and investigate the presence of outliers. This step was essential in selecting the appropriate geostatistical modeling procedure (Kim 1988).

The spatial behavior of DGW was characterized by constructing experimental semivariograms. An appropriate model was fit to the experimental semivariogram using mathematical parameters. Correct model parameters were considered important factors in generating reliable estimates as mentioned in Deutsch & Journel (1998). The OK system was then employed to generate griding points and to build the geostatistical model for the spatial extent of the water table.

Results

A straight line on a normal-probability plot reflects the statistically normal behavior of the data set as shown in Fig. 3. Horizontal experimental semivariograms along four principle directions are shown in Fig. 4. These semivariograms represent the spatial behavior of the DGW variable along N-S, N45E, E-W, and S45E directions. Isotropic behavior was assumed; hence, an average single semivariogram has been considered for model-fitting purpose. A linear mathematical model was fitted to the experimental semivariogram with the following parameters: nugget variance of 1.72 cm^2, model power value of 1, and model slope of 0.59.

he modeled domain was divided into 0.375 x 0.375 m cells at which the DGW values were estimated by the OK procedure. The generated map for the shallow groundwater system surface is shown in Fig. 5. The depth to water table is estimated at about 68 cm below ground surface in the E & SE regions and about 65 cm at the NW regions. The estimated hydraulic gradient is about 0.001 from W-NW to E-SE. To evaluate OK model results, a model estimate at a specific location (trench) was compared to a field measurement. The estimated DGW value was 66.4 cm while the field observation value was 68 cm with an estimation error of 2%. This departure may be referred to moisture content rise within the capillary fringe of the unsaturated zone.

Conclusions

Results of this study indicate that the spatial extent of shallow groundwater surface has been estimated reliably. The modeled watertable has been obviously imaged at depths between 65 cm and 68 cm, which approximately in agreement with field observations. This conclusion reflects the reliability of the tested approach to generate a detailed map for the surface of a shallow groundwater system. The application of this method may be considered in large scale projects to explore new groundwater resources and define the extent of contaminants in shallow aquifers.

Acknowledgement

This study was supported by the Applied Research Income Grant no. ARI-017, King Fahd University of Petroleum and Minerals (KFUPM), Saudi Arabia.

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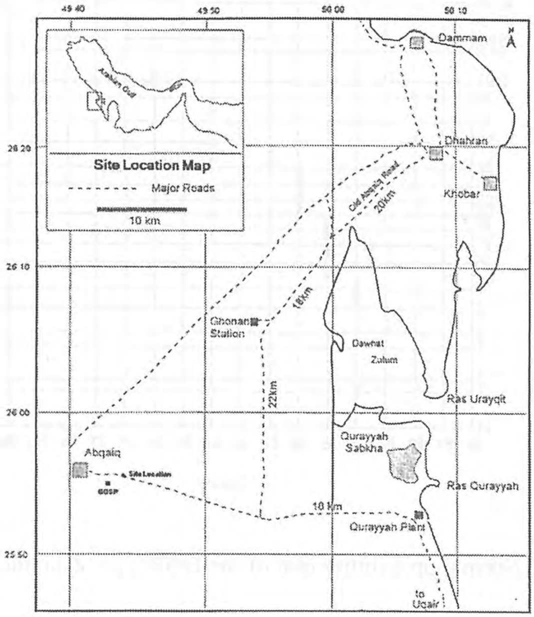

Figure 1: Location map of the study area

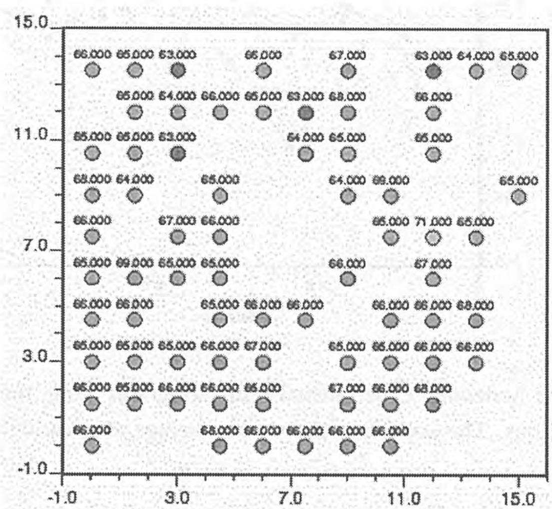

Figure 2: Plan view of the “imaginary monitoring wells - IMW”. The number on top of each IMW indicates the DGW surface detected by the GPR.

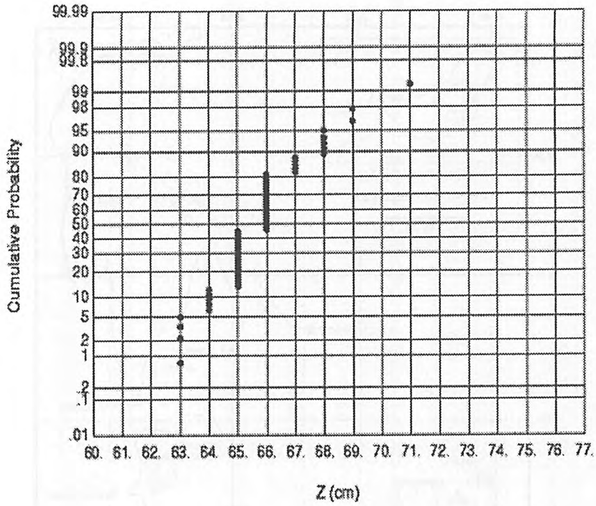

Figure 3: Normal probability plot of the DGW (i.e. Z in cm) data set

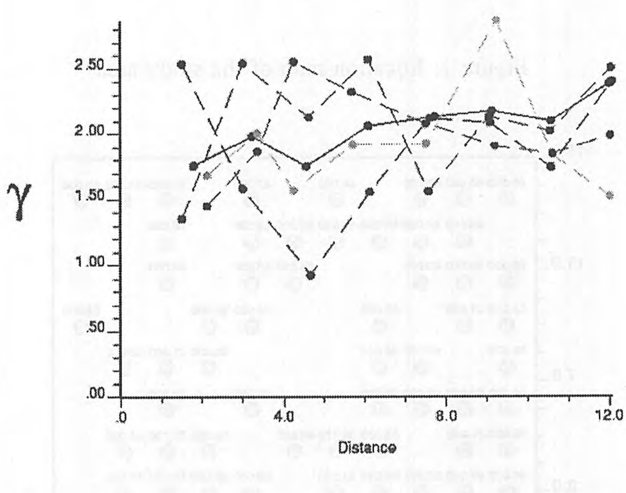

Figure 4: The horizontal experimental semivariograms along four principle directions. The solid line shows the average semivariogram.

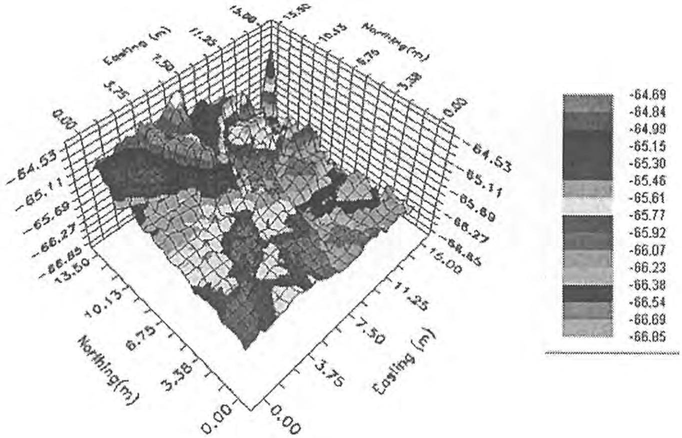

Figure 5: A 2D map of DGW visualizing the spatial extent of the water table and soil moisture in the study area. Negative numbers in the vertical axis show the DGW.

A Hydrogeological and Quantitative Groundwater assessment of the basaltic aquifer, Northern Harrat Rahat, Saudi Arabia

Abdulaziz Al-Shaibani , John W. Lloyd,
Abdulwahab A. Abokhodair and
Abdulwahab Al-Ahmari

A HYDROGEOLOGICAL AND QUANTITATIVE GROUNDWATER ASSESSMENT OF THE BASALTIC AQUIFER, NORTHERN HARRAT RAHAT, SAUDI ARABIA

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ABSTRACT

The Northern Harrat Rahat consists of 300m of basalt lavas covering some 2,000 km^2 to the south-east of Al-Madinah in western Saudi Arabia. Like many basalt sequences, the Rahat basalts form an important aquifer and groundwater resource. The aquifer has a saturated thickness of up to 60m and is made up of the weathered upper part of underlying basement, pre-basalt sands and gravels, and the fractured basalts. Since 1992, groundwater has been abstracted from the aquifer as part of the Al-Madinah water supply. To assess the potential of the aquifer, an assessment has been made based on pumping tests of about 70 wells. The hydraulic parameters have been shown to be highly variable, typical of the fractured domain. The aquifer contains good-quality water in storage, but receives limited recharge. Groundwater temperature anomalies indicate remnant volcanic activity locally. A numerical groundwater model has been constructed, which has been calibrated using limited groundwater head measurements, but with good abstraction records. Predictions of groundwater heads and the examination of several abstraction scenarios indicate that the aquifer can continue to support part of the Al-Madinah demand for the next several years, if certain well distributions are adopted. The predictions also show that the aquifer can only support the total demand of the city for a few days as a contingency resource.

Keywords: Basaltic aquifers, groundwater resources, Saudi Arabia

INTRODUCTION

The study area is the northern part of Harrat Rahat, to the immediate southeast of Al-Madinah Al-Munawwarah, and covers an area of approximately 2,000 km^2 (Figure 1). Groundwater occurs in an aquifer composed of basalt lavas and underlying alluvium and weathered basement. Within the area are three wellfields providing part of theAl-Madinah water supply. A number of geological and hydrogeological investigations have been carried for in the Al- Madinah region, some of which relate to the study area. Detailed geologic mapping of the area includes work by Pellaton (1981), Moufti (1985), and Camp & Roobol (1991). A number of regional hydrogeological studies have been carried out and have been summarized by Bayumi (1992), who investigated the hydrogeology of the Northern Harrat Rahat.

The geology of the basalts is reasonably well detailed as is the composition of the aquifer. The extent of the aquifer to the east and the south of the study area, however, is not fully understood due to the absence of hydrogeological information.

Abstraction from the aquifer started in the early 1970's, but between 1990 and 2000, three wellfields were constructed to supply Al-Madinah with water. Significant head declines have occurred in the northern part of the area as a result of over-abstraction and many of the wells in the northern fields have dried up. The study described below has been carried out to examine the extent of the over-abstraction, to improve the understanding of the aquifer and to test alternative abstraction scenarios.

Basalts form some of the most difficult aquifers to evaluate because of the inherent variability in their hydraulic properties. Available data were used to form a conceptual model of the aquifer by defining the hydrogeologic framework and evaluating the hydraulic characteristics. The data were also used to determine the water budget and evaluate the hydrochemistry. Finally, a regional groundwater flow model, focused upon the existing wellfields, was constructed and used to test management alternatives based on water requirement data.

GEOLOGICAL SETTING

Physiography and Drainage

The lava fields of the western part of the Arabian Peninsula comprise one of the world's largest alkali volcanic provinces with an approximate area of 180,000 km^2. They were pro-duced by the continental intra-plate volcanism accompanying the opening of the Red Sea (Camp and Roobol, 1991). The Harrat Rahat lava field is one of the largest components of this continental basalt province and forms a major topographic feature extending from Al Madinah Al Munawwarah in the north to the northern outskirts of Jeddah and Makkah in the south. It measures about 310 km north-south and 75 km east-west; a total area of 19,830 km^2.

The harrat has an irregular sub-basaltic topography consisting of basins that are elongated along the length of the harrat. Two main wadis existed before the volcanic eruptions as inferred from geophysical investigation (Daessle and Durozoy, 1972). Both wadis flowed northwards towards what is now the Al-Madinah city area. New drainage evolved after the initial extrusion and was modified as eruptions took place until the present-day system developed. Currently, there are two major wadis draining a combined watershed area of about 4500 km^2 and collecting about $260x10^6$ m^3 of rainfall annually.

Local Subsurface Geology

Harrat Rahat has evolved over the past 10 million years and is composed of three stratigraphical units separated by two disconformities: the Shawahit (10 - 2.5 Ma), Hammah (2.5 to 1.7 Ma), and Madinah (1.7 to Recent) ba-salts (Camp and Roobol, 1991).

Two main basaltic layers 150-200m thick have been identified, overlying the basement. They are distinguished by their color – a light gray upper layer and dark gray to black lower layer. The upper layer is consistently within the top 70 – 100 m section. The two layers correspond to Madinah (upper layer) and Hammah basalts. Sand and gravel is present locally immediately above the bedrock with some very fine sand and clay layering in basalt inter-flow zones.

HYDROGEOLOGY

While the general geology of the area is reasonably well understood, the hydrogeological data are limited in distribution. Some groundwater table elevation data, abstraction, and well test information are available for three wellfield areas that are about 10 km apart, but away from these areas only limited data are available, principally at the margins of the aquifer system. To extend the limited and localized database, four exploratory wells were drilled as part of the present study. The data from those wells helped in completing the contour maps of bedrock elevation and alluvial deposits and basalt thicknesses.

Aquifer System Definition

The geological sequence and aquifer are shown conceptually on the left of Figure 2. The aquifer definition is based upon an interpretation of the well records. The main producing zone consists of: (1) the topmost weathered part of the 'basement', generally less than 5 m thick, (2) the sub-basaltic gravels and sands deposited on the pre-lava ground surface, and (3) densely fractured, jointed, and vesicular basalts that characterize the lower part of the lava sequence. The base of the aquifer is the bottom of the 'basement' weathered zone.

The top of the aquifer is regionally a free water surface. Minor semi-confined zones occur caused by the presence of thin layers of low permeability material and variations in lava and inter-lava hydraulic characteristics.

For undisturbed conditions (i.e. non-abstraction conditions), the saturated thickness of the system ranges from 50 to 60 m. The sub-lava and inter-lava flow alluvium varies in lithology from clay to sands and gravels, and is of variable extent and thickness. The presence of fine- grained inter-beds in places may impede groundwater flow locally, and may be a possible explanation of the low productivity of some wells.

Groundwater Head Distribution and lateral boundaries

Pre-development (steady state) water levels

It is considered that prior to abstraction, the aquifer system was in a state of dynamic equilibrium. The drilling of deep wells started in about 1967 with exploratory wells. 1970 probably marks the year when the aquifer started to be developed. Few groundwater head data exist for the pre-1970 period; consequently, the pre-development head distribution has been based initially on a combination of scattered well data compiled by Bayumi (1992) and data interpolated from later wellfields. The distribution is shown on Figure 3, and has been derived finally, iteratively from the groundwater model discussed below.

From the head distribution in Figure 3, certain hydrogeological features are apparent. A groundwater divide occurs coincident with the topographical divide in the east demarcating a no-flow flow boundary to the system. A broad groundwater divide is present in the south trending generally east-west. In the extreme south of the study area, under undisturbed conditions (i.e. non-pumping), groundwater head indicates south-westerly flows. The control for these flows is the wadis and sebkhas of the Wadi Al-Yatimah to the south of the study area. In the west, in the Wadi Al-Aqiq, the heads accord with flow to the north in the direction of the down-gradient of the wadi, demonstrating that the system along this boundary is drained by the wadi alluvium. Heads in the north indicate a westerly groundwater flow consistent with the presence of the Al-Madinah springs that have been the historical northerly drainage point for the aquifer system in that area. The two groundwater divides define the principal part of the aquifer system in which heads decline variably from the south-east to the north and north-west.

Transient Groundwater Heads

Heavy abstraction has occurred since about 1975. Declines of up to 10 m in the groundwater levels were observed in the north over a period of about 20 years (Bayumi, 1992). The rate of abstraction probably exceeded 12 x10^6 m^3/year by 1990 and was concentrated in the northern parts of the aquifer.

As a result of declining heads and yields in the northern wellfields, a further wellfield was drilled in the Abar Al-Mashi area, consisting of three well groups. Pumping of the wellfield commenced in 1992 and, where feasible, the wellfield has been operated since that date. Figure 5 shows a south-to-north cross section of elevations of ground surface, water levels, and bedrock.

Aquifer Characteristics

Pumping Tests Results

The complex, fracture dominated character of the aquifer has led to difficulties in performing and interpreting pumping tests. The parameter range deduced from testing is considerable, with transmissivity ranging between 13,300 and 1 m^2/day, and storage between 0.3 - 0.00031.

In considering the parameters, various hydrogeolgical factors need to be stressed. Most of the data relate to pumping well data that cannot strictly be analyzed for transmissivity and certainly cannot be analyzed for storage. Where transmissivity interpretations are applied to pumping well data, the results tend to significantly under-estimate transmissivity. Further, radial theory used in pumping test interpretation is of doubtful applicability in secondary permeability systems. Some pumping tests resulted in no drawdown for significant pumping discharges, providing strong evidence of localized very highly transmissive zones. Some wells with similar designs, in close proximity, gave markedly differing well yields during production testing, further demonstrating flow path complexities and the typical difficulties of obtaining definitive aquifer characteristics for lava aquifers.

The data provide no clear pattern in spatial transmissivity distribution. Conceptually, the highest hydraulic conductivities would be expected in the lowermost lavas, which are the oldest, the most widespread, and which have been subjected to weathering conditions more than later lavas. These lavas were the most viscous of the lava pile and therefore most prone to fracture. Additionally, they will have been the most affected of the lavas in terms of minor seismic activity. The younger lavas, mainly present in the east, were less viscous on extrusion and therefore less prone to fracture, inferring a lower potential for porosity. In the eastern high elevation, volcanic cone area, the older fractured lavas exhibit veining associated with later volcanic activity. In this area, therefore, it is considered that any initial porosity would have been radically reduced. It is concluded that the regional transmissivity distribution is therefore likely to be low values in the east with higher values in the west.

In view of the absence of any reliable data of specific yield from well testing, reliance for storage understanding was placed upon the interrogatory modeling of regional drawdowns, which in fact provides far better insight than individual well complex testing. The storage values are discussed below in the numerical modeling.

Groundwater Flows

The general groundwater flow direction in the system is to the north and northwest with the discharge historically to the Ayn er Zerqa springs at Al-Madinah, and alluvium in the Wadi Al-Aqiq (west) and the Wadi Al-Hamdh (north). Groundwater has accumulated in time through recharge from rainfall, runoff, and from subsurface groundwater flow from the south, outside of the study area. Natural discharges from the system occur through alluvium in fringing wadis and the system has been stressed by abstractions.

The area is arid with the current aridity cycle probably having been a feature for the past 8000-6000 years. Highly variable rainfall frequency and small amounts are typical. When combined with an extremely high evaporation potential, effective direct recharge through the soil profile from rainfall, is precluded. Potential evaporation is in excess of 2m annually, which compares with an annual rainfall mean of 63mm.

The broken surface of the lavas allows indirect recharge to occur; however, data are unavailable to allow a direct assessment, as the measure of such recharge poses immense hydrological difficulties. An estimate of recharge of about 10% of annual mean rainfall has been used as an initial guide and has been tested in the model described below.

The concept of natural discharges to alluvium in the fringing wadis is rational but not quantifiable from the field data. As with most other flows in the system, these discharges have been examined through the groundwater modeling.

Abstraction data prior to 1970 is fragmentary. Annual discharge in the Al-Madinah general area is estimated at about 70 million m^3/year in 1970 and 34.10^6 m^3/year (net of irrigation return) from about 1145 wells for 1979 (Italconsult, 1979). Both the number of wells and the annual abstraction has increased since. Three wellfields have been operated for the city supply since 1992, producing a combined average of 43,000 m^3/ day. 60 private wells were surveyed for the present study with an estimated production of 21 x 10^6 m^3/year.

GROUNDWATER QUALITY

The groundwater quality is currently suitable for both drinking and agriculture. Higher temperatures and slightly higher chloride concentrations encountered at depth in some eastern wells indicate ongoing volcanic influences.

GROUNDWATER RESOURCES APPRAISAL

Approach adopted

The resources potential for the aquifer has been assessed using the United States Geological Survey finite difference groundwater flow model MODFLOW (Macdonald and Harbaugh, 1988, USGS, 2000). The concepts described above have been incorporated as relevant using an iterative approach. Information from the wellfield has been the dominant factor. The hydrogeological database, as demonstrated above, is limited in distribution. The model representation achieved, and discussed below, cannot be considered to be truly definitive; however, it does provide a means of understanding bulk performance of the aquifer with respect to future water demands. The lack of definition (detailed description of the different parameters) is typical for a groundwater system in an arid area that has been developed progressively from a practical resources point of view.

MODELLING ASSESSMENT

Model Framework and Boundaries

For modeling a single layer representation was adopted using a north-south, east-west grid of 50 x 55 cells of 1km x 1km cells (Figure 4). The cell sizing was modified so that a highest density covers the wellfield areas.

The major eastern groundwater divide was assigned as a 'no-flow' boundary. For the southern boundary of the model the current study area boundary has been used for convenience. No hydrogeological data exist within any reasonable distance to the south of this boundary, although the lavas extend for some distance. A 'general head ' boundary condition has been used, permitting two-way flow. Accepting the premise that the aquifer system drains naturally to the alluvium in the fringing wadis (Figure 1), 'drain' boundaries have been applied as shown in Figure 7 in the west and in the north of the model. In the extreme south-west and extreme north-west, 'no-flow' boundaries have been applied, where the aquifer system abuts directly against basement rocks.

The lower boundary has been defined as a 'no flow' boundary. The system is unconfined, so that a free water surface is calculated within the model, defining the upper boundary.

Procedure

Any groundwater modeling analysis is an iterative examination of the various parameters controlling groundwater flow. The procedure is dependent upon field data and an interpretation of the hydrogeological conditions. Assumptions are inherent in the procedure and require testing on a trial basis. Flows are the most important element in understanding the system which can pose problems in arid areas, because base flows rarely occur and recharge is not understood in any definitive sense. The groundwater heads that reflect flows are therefore used as a guide to understanding of the system and its modeled representation.

Calibration

The procedure used in the study was to model an approximate 'steady state' condition reflecting the conceptualized pre-development groundwater head distribution. This was used to obtain an approximate understanding of the main flow inputs and outputs for the system and to produce a head distribution that could be assigned as the initial values for the 'transient state' modeling. The head distribution shown on Figure 3 reflects this phase of the modeling.

For the transient calibration, the period 1970 to 2001 was adopted, with the assumption that no meaningful abstraction occurred prior to that period and that the specified heads approximated in the 'steady state' analysis could be used as initial heads.

In MODFLOW, specifications are required for the time interval flow calculations that include 'stress period' and 'time step' values. These values were arranged so that the model outputs could be judged for specified years from a daily output, maintaining, however, numerical stability in the solution. The 'transient state' was examined in the conventional manner by inputting parameter matrices and modifying these on a 'trial and error' basis. The principal calibration control used was individual representative heads for the three wellfield groups. Dependable data from observation wells that does not reflect very localized pumping is only available for 1992 and 2001-2002. These data are shown on the head calibration in Figure 8.

Parameter Inputs

The hydraulic parameters were eventually determined iteratively. Low hydraulic conductivities (K) have been assigned in the east (0.01 to 6 m/d) and high values in the west (7 to 40 m/d) in keeping with the concept discussed above. A similar approach was adopted for specific yield (S_y) - 0.05 to 0.08. Because of the problems noted above for determining hydraulic characteristics in lavas, it is difficult to assess the veracity of the values derived. However, the characteristics portray regionally a moderately high transmissive aquifer with a smallish specific yield, consistent with what would be expected in a fractured basalt medium. At the 'drain' boundaries a simple rule was applied setting drain base to about 50m below wadi ground elevation. For realization, the boundary uses a conductance term, reflecting drain permeability and flow convergence. The flow of groundwater to the drain is controlled mainly by the conductance. A conductance is also required for the 'general head' boundary. Conductance values for both drain and general head boundaries were derived iteratively.

Refined recharge input ranged between 4 and 10 mm/year. The values are small as would be expected, with the highest recharge assigned to the highest topography.

As applicable, a pumping schedule was applied to the wellfield based upon a very good record of abstractions. Most of the abstraction data were recorded daily for each well and assigned to the appropriate wells in the model.

Groundwater Head Distributions Derived

As a result of the transient state data testing, a sequence of groundwater head distributions were obtained for the 1970-2002 period. The system distribution for 2002 is shown on Figure 5. On Figure 6 the relationship between the representative field heads for the well groups in the 3rd wellfield are compared with the model generated heads.

Comments on the Calibration Results

For the calibration, it is essential that it be borne in mind that the aquifer has been operated for the practical purposes of water supply. The aquifer has not been researched historically with a view to an aquifer system analysis so that the database for a definitive analysis is not available. It is further stressed that the type of aquifer, which is dominated by lava flows, is one of the most difficult to evaluate. Nevertheless, good bulk abstraction data are available, together with some limited relatively undisturbed head data. The influence of the abstraction has been adequately represented in the calibration and gives confidence that the regional aquifer characteristics are of the right order. It therefore follows that the flow balances derived are reasonable and that, despite the assumptions inherent in the type of modeling carried out, the calibrated model provides a tool for examining future abstraction potential.

Sensitivity Analysis

Sensitivity of the model heads was tested by individually and simultaneously changing K and S_y by ±20%, ±40% over the calibrated values. An example is shown in Figure 7. The model is reasonably sensitive to changes in K but the solution becomes unstable when S is increased or decreased by more than 20%, and the solver parameters had to be changed for the solution to converge. The best agreement between simulated and measured heads was obtained with the original (calibrated) values of K and S_y. These sensitivity results are important in showing that the model is sensitive to S_y in that the aquifer supply is dependent upon storage.

Management Alternatives

Water supply demand for Al-Madinah is expected to reach 375,000 m^3/day by 2010, and 460,000 m^3/day by 2015. The bulk will be met by desalinized water but there will be a shortfall which, if feasible, will be taken from the aquifer. Further, it is important to understand the extent to which the aquifer can support demand in the event of temporary failure of the desalinized water supply.

To examine whether the aquifer could support the expected demand shortfall, several abstraction scenarios have been tested. The scenarios are: (a) abstract the shortfall entirely from the current operational wells in the field, (b) abstract the shortfall from a well configuration embracing the wellfield and adjacent areas, and (c) abstract all of the city's water demand from the current wells in case the desalinized water is partially or completely discontinued. The first scenario was selected from an operational standpoint, while the second scenario was examined with consideration to distributing the abstraction and the consequent drawdown impact on the aquifer. The third scenario is a short-term contingency plan.

Future Scenario Results

In the simulation modeling for the first two scenarios, the abstraction demands have been introduced for the period 2002-2032, following the calibration period 1970-2001.

For Scenario 1, abstractions were assigned to the producing wells of the wellfield and the total abstraction amount is divided equally among the wells. The simulation results for the scenario show that the aquifer sustainability will become critical in about 2010. The demand, however, should be met at least to this date even if no alternative scenario is adopted, and it may be concluded that sufficient aquifer potential exists to allow time for decisions related to alternative supply sources to be made.

For Scenario 2, the distribution of abstraction has been changed from Scenario 1 in order to examine the potential of the aquifer with a less concentrated drawdown impact. A different configuration of abstraction wells and a different abstraction schedule were used for Scenario 2. All wells are located in the general area hosting the wellfield. The impact of pumping on the aquifer is less in Scenario 2 compared to Scenario 1, because abstraction is more distributed (Figure 8). The simulation results for Scenario 2 show that the aquifer sustainability will become critical in about 2014. The demand, however, should be met that year, even if no alternative scenario is adopted.

Scenario 3 examined the hypothesis where part or all of the desalinized supply becomes temporarily unavailable and the total supply has to be abstracted from the aquifer system. Three cases were tested and are summarized in Table 1. In the scenario, the total abstraction (amount lost from desalinated supply + current well field supply) in each case is distributed equally among the wells used in Scenario 2. In Case 1, where only part of the desalinized water supply discontinues, the amount assigned to each well is 2,300 m^3/day, assuming it is practically possible. Reserve wells may have to be drilled. It appears that the aquifer can support this demand for the three periods.

In Case 2 where 200,000 m^3 are required, aquifer support for only 3 days would appear likely. For more than 3 days, there will be significant declines in the water level, many wells will dry up, and the aquifer could be depleted in the wellfield area. Again, the current wells with the current production of about 1000 m^3 each cannot provide the required volume for the case. Some 100 more reserve wells would be needed, if the contingency were to be feasible. Case 3 was not tested for the reasons noted for Case 2.

Case	Incident	Amount lost (m^3)	Total Abstraction (m^3)	Duration	Can aquifer support demand?
I	First Line discontinued	80,000	130,000	• 3 days • 15 days • 30 days	Yes Yes Yes
II	Second Line discontinued	200,000	250,000	• 3 days • 15 days • 30 days	Yes No No
III	First and second Lines discontinued	280,000	330,000	• 3 days • 15 days • 30 days	No No No

Table 1. Emergency abstraction plans during a temporary halt in the desalinized water supply.

Aquifer Potential as a Water Storage Facility

Both field observations and groundwater model show that the aquifer is being over-exploited and if current operations continue will become virtually redundant. Further, a poorer quality groundwater is being drawn to the system from the east. However, the aquifer does provide a proven groundwater storage facility that could play an important role in an integrated water resources management scheme whereby excess desalinated water and/or treated wastewater could be recharged into the aquifer and recovered when demand dictates.

The location of the aquifer close to Al-Madinah, with the infrastructure of wells and pipe network, provide an overall facility that would be worth testing for storage and retrieval purposes in order to prolong the aquifer life and provide a strategic reserve for Al-Madinah.

Conclusions

A basalt aquifer system covering 2000 km^2 has been defined in the northern part of Harrat Rahat close to Al-Madinah Al-Munawwarah. The main producing zones consist of: (1) the topmost weathered part of the basement, (2) the sub-basaltic gravels and sands of the pre-lava surface, and (3) the fractured, jointed, and vesicular lower part of the lava sequence.

Under undisturbed conditions, the saturated thickness in the study area ranges from 50 to 60m. The aquifer system has been described in regional terms because of the complexity of the lava hydraulics and the lack of detailed data. However, the regional interpretation is considered suitable for groundwater resources purposes.

Prior to the mid-1970's when abstraction commenced, the aquifer was in a state of equilibrium. Random well drilling occurred and three major wellfields were constructed for the Al-Madianh water supply. The rate of abstraction has exceeded the amount of recharge.

Groundwater quality is suitable for both drinking and agricultural purposes. Higher water temperatures and relatively higher chloride concentrations exist in the east indicating ongoing volcanic influence.

The groundwater resources potential of the aquifer system has been assessed using a numerical groundwater model. Three possible abstraction scenarios for future management have been tested which indicate that the aquifer can support the Al-Madinah demand up to about 2010 using the current well configuration. The aquifer can support the demand, however, for more several years, if more wells are drilled. A contingency scenario tested to determine the ability of the aquifer to support the Al-Madinah in the event of problems with the desalinated water supply found that with the current well distribution, the aquifer can support the total demand for only a few days.

Acknowledgements

The authors would like to thank the King Fahd University of Petroleum and Minerals for its support. The Al-Madinah Water Directorate supported this study and provided most of the data. The help of Jowaher Raza, Mohammad Fargali, and Mamdouh Raddadi is appreciated.

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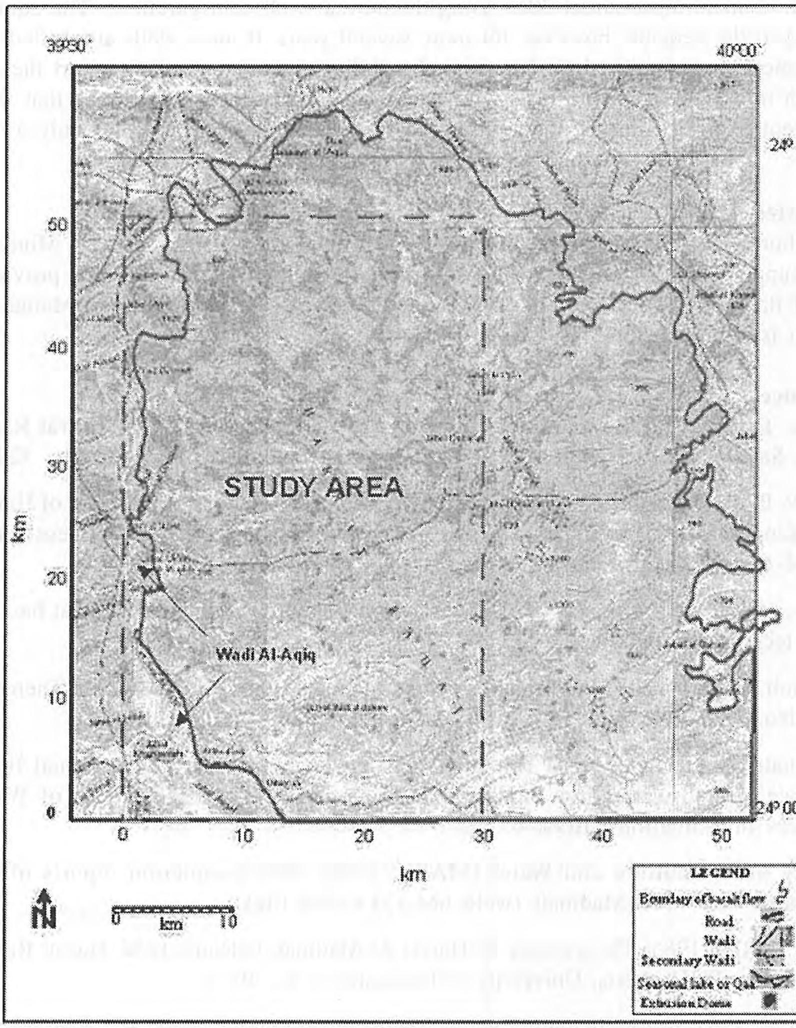

Figure 1: Location and limits of the study area. Zero reference for the study is 24°00´ N, and 39°32´ E

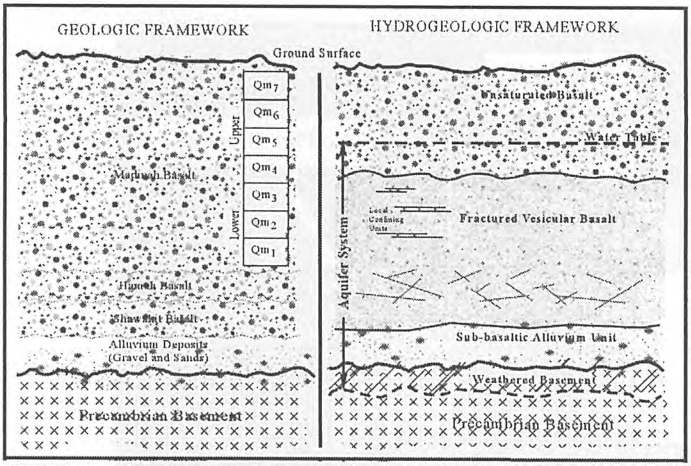

Figure 2: Correlation between geologic and hydrogeologic frameworks in northern Harrat Rahat

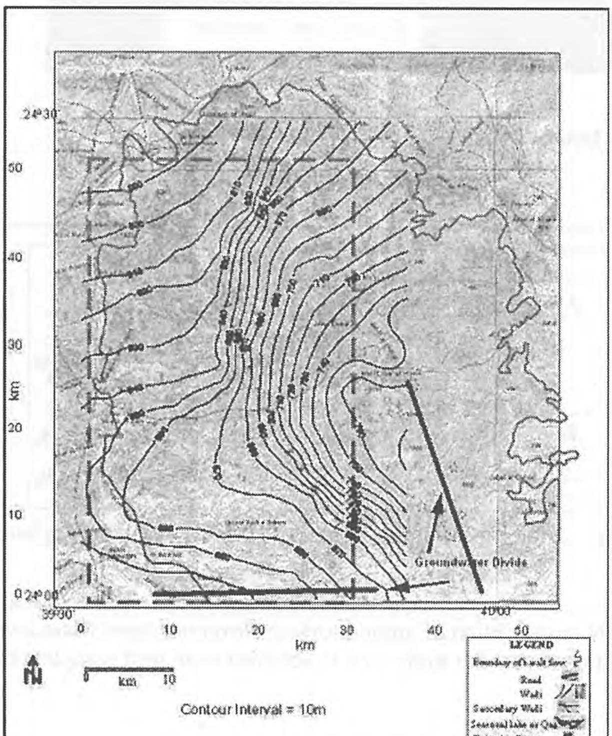

Figure 3: Predevelopment (pre~ 1970) water levels.

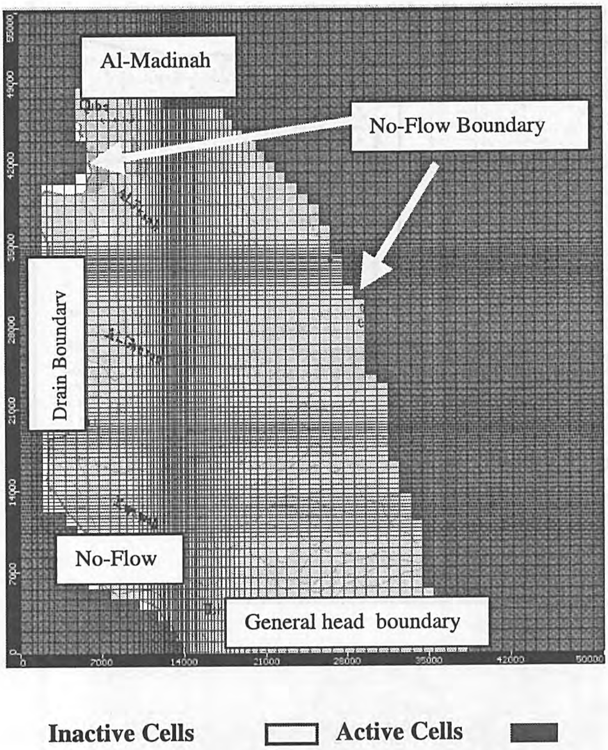

Figure 4: Model grid and boundaries.

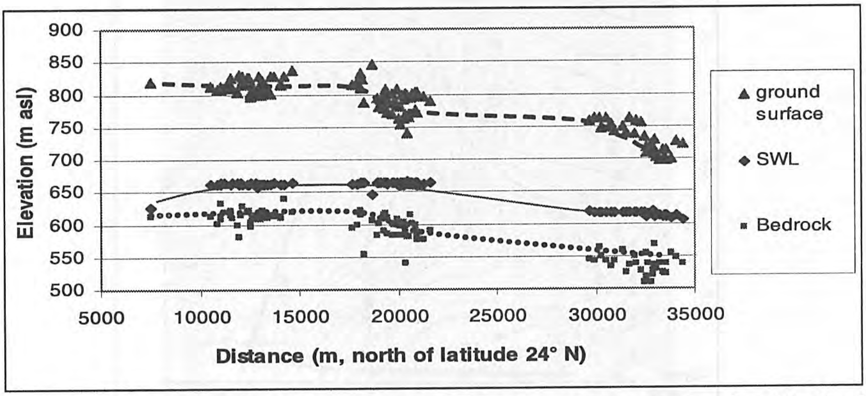

Figure 5: S-N cross section of ground surface elevation, static water level, and bedrock elevation across the study area as obtained from well completion reports.

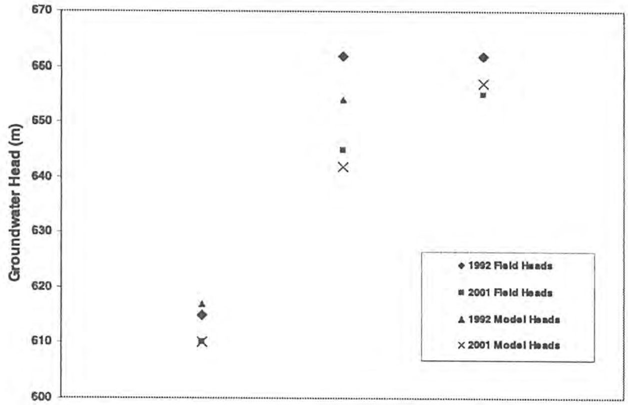

Figure 6: Comparison of field and model heads (m asl) at the three well group locations for 1992, and 2002.

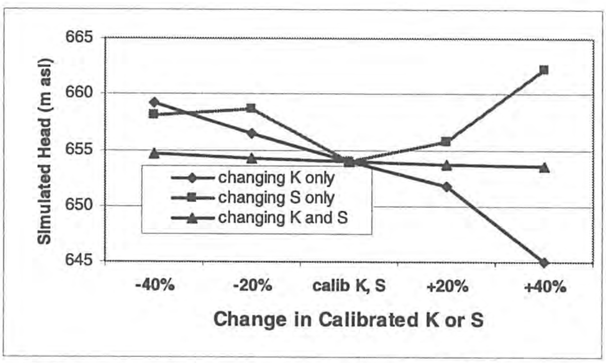

Figure 7: Sensitivity analyses where changes in simulated 1992 head are plotted versus changes in calibrated K and S.

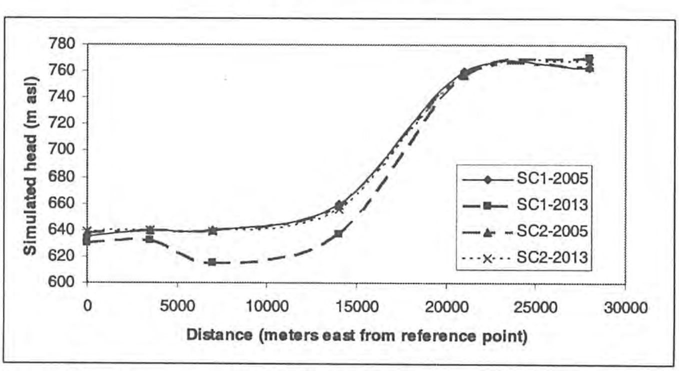

Figure 9: Water table across the wellfield (W-E) as simulated in scenarios 1 and 2, for 2005, and 2013.

Relationship between excessive production rate and produced groundwater quality

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RELATIONSHIP BETWEEN EXCESSIVE PRODUCTION RATE AND PRODUCED GROUNDWATER QUALITY

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ABSTRACT

Ground water is a vital source for fresh water in Saudi Arabia and the surrounding Gulf Countries. It is well known that fresh water density is lower than that of saline water containing appreciable amounts of dissolved salts. Therefore, water quality in the top of the aquifer is superior to the water in the bottom of the aquifer due to the effect of density and gravity segregation. Normally, there is a margin of separation between fresh and saline water known as the fresh water-saline water contact. Producing fresh water (from the top of aquifer) by excessive pressure drawdown forces the saline water to move faster towards the producing wellbore in a process called upconing. The top of the cone (maximum height) is function of pressure drawdown (pumping). Several incidences have been reported indicating that the quality of groundwater in many wells in the Kingdom of Saudi Arabia has deteriorated perhaps due to saline water upconing caused by high pressure drawdown. Therefore, pressure drawdown must be carefully selected so that good quality fresh water is produced without upconing the saline water into the producing wellbore. In this study, a general equation governing the water upconing process in groundwater wells is presented. The water upconing process is examined on a Saudi groundwater aquifer. Furthermore, a comparison study is made for pressure drawdown using vertical and hypothetical horizontal wells producing from the same aquifer. Thus, optimum pressure drawdown reduces the degree of fluid disturbance (upconing and saline water intrusion) that may occur due to high pressure drawdown caused by excessive water production from aquifers.

Keywords: Groundwater, Aquifer, Upconing, Horizontal well, Pressure drawdown, Water quality, Saline water.

INTRODUCTION

Saudi Arabia (2.25 million square kilometers) in general is one of hottest and most arid countries in the world, with an average maximum summer temperatures of 46°C and an average rainfall of 120 mm/year. Water resources in Saudi Arabia are conventional which includes groundwater and surface water, and non-conventional such as desalinated seawater and treated wastewater. 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 aquifers in Saudi Arabia [2]. All wells drilled in these formations for groundwater production are vertical [3]. Aquifers listed in Table 1 were formed millions of years ago. Most of these aquifers are not receiving recharge at the present leading to depletion and water quality deterioration with time [4]. Water deterioration can be attributed to natural saline water intrusion or saline water upconing caused by excessive drawdown.

DRINKING WATER QUALITY

Water fit for human consumption should not contain constituents which would affect its color, odor or appearance. It should be free from foreign bodies such as soil, sand and impurities that are visible to the naked eye. The total hardness should be less than 500 ppm [5].

Incidences have been reported indicating that the groundwater quality in many parts of the Kingdom of Saudi Arabia are deteriorating due to saline water upconing caused by high pressure drawdown. For example, the quality of groundwater produced from Neogene groundwater aquifer in Al-Hassa in the eastern province deteriorated sharply due to saline water intrusion [6]. Similar situations were observed in the Ha'il aquifers [7] and in the central province in the Minjur aquifer [4] due to excessive pressure drawdown (pumping).

OBJECTIVE OF THE STUDY

The objective of this study is to present an engineering method that can be utilized for the prediction of optimum fresh water production rates with no saline water intrusion (upconing) in both vertical and horizontal wells. This method is presented in the following section.

WATER UPCONING THEORY

Upconing is a term used to describe the mechanism underlying the upward movement of high salinity water into the producing well. Upconing can seriously impact fluids distribution caused by density and gravity action over millions of years in aquifers. Once this equilibrium is disturbed, it needs a very long time for these fluids to regain their initial equilibrium.

Upconing is primarily the result of movement of high-density water (saline water) in the direction of least resistance towards the vertical or horizontal production wells as shown in Figures 1 and 2 [8 and 9]. For vertical wells, water upconing is highly dependent on specific gravity difference (Äg, dimensionless) between fresh water (g_{w1}, dimensionless) and saline water (g_{w2}, dimensionless), formation average permeability ($\bar{k}$, Darcy), radius of the drainage area (r_e, m), wellbore radius (r_w, m), depth of wellbore penetration into the fresh water zone (d, m), fresh water viscosity (m_w, cp), water formation volume factor ($?_w$, dimensionless) and fresh water zone thickness (h, m). By the combination of the above parameters, critical production rate in vertical wells (Q_{vc}, m^3/day/well) above which saline water upconing occurs, can be calculated as follows:

$$Q_{VC} = 0.801 \frac{\bar{k}\,\Delta\gamma\,(h^2 - d^2)}{\mu\,\beta_W\,\ell n\left(r_e / r_W\right)} \qquad \ldots(1)$$

For horizontal wells, additional factors are considered such as half of the major axis of drainage area (a, m), length of the horizontal well (L, m), horizontal well drainage radius (r_{eh}, m) and effective wellbore radius (r_{we}, m). Similarly, by the combination of the above parameters, critical production rate in horizontal wells (Q_{hc}, m^3/day/well) above which saline water upconing occurs, can be calculated as follows [8]:

$$a = \left(\frac{L}{2}\right)\left[0.5 + \sqrt{0.25 + \left(2r_{eh}/L\right)}\right]^{0.5} \qquad \ldots (2)$$

$$r_{we} = \frac{r_{eh}\left[\frac{L}{2a}\right]}{\left[1 + \sqrt{1 - [L/(2a)]^2}\right]\left[\frac{h}{2r_w}\right]^{\left(\frac{h}{L}\right)}} \qquad \ldots (3)$$

$$Q_{hc} = 0.801 \frac{\Delta\gamma \bar{k}\left(h^2 - d^2\right)}{\mu \beta_w \, \ell n\left(r_{eh}/r_{we}\right)} \qquad \ldots (4)$$

*F*rom equations 1 and 2, it can be observed that the height of a saline water upcone (h minus d) is directly proportional to the magnitude of the production rate (i.e. pressure drawdown) as shown in Figures 1 and 2 for vertical and horizontal well respectively. Equations 1 and 2 were used to predict water upconing in the Wasia aquifer based on the technical data presented in Table 2. It must be noticed that fresh water-saline water contact (interface) and densities must be measured accurately using well logging tools and chemical analysis respectively in order to get realistic predictions of saline water upconing using the above equations.

RESULTS AND DISCUSSION

Water upconing analysis for the Wasia aquifer was performed based on the technical data presented in Table 2. Figures 3 and 4 show the relationship between fresh water production rates, saline water upconing height (h-d), length of wellbore penetration into the fresh water zone (d) and fresh water zone thickness ratio (d/h). It can be seen that as the penetration of the wellbore into the fresh water zone increased more saline water will upcone into the production wellbore and mix with the fresh water causing poor water quality production. Therefore, for good water quality production, the wellbore penetration into the fresh water zone should be kept at a minimum.

During fresh water production, saline water upconing effect will be small if the average permeability of the aquifer is high enough to allow for fast fresh water recharge from the surrounding drainage area. By doubling the value of aquifer average permeability, the critical fresh water production rate with no upconing is also doubled as shown in Figure 5. Thus, high fresh water production rates can be applied in high permeability aquifers. Similar effect on fresh water production rate can be noticed due to the difference between the specific gravities of the fresh water and the saline water as shown in Figure 6. Higher saline water specific gravity yields higher gravity (weight). Therefore, higher fresh water production rates can be applied when high specific gravity saline water exists below the fresh water.

It is well known that a horizontal well yields a similar or more productive rate, as four vertical wells yield, based on h/L ratio from identical drainage areas of the same pressure drawdown as shown in Figure 7 [3]. Therefore, higher fresh water production rates with no saline water upconing can be applied in horizontal water wells as shown in Figure 8. More details about the utilization of horizontal well technology in groundwater projects are documented in reference 3.

ECONOMICAL FEASIBILITY

Horizontal drilling technology has advanced tremendously over the past twenty years. Drilling costs have dropped markedly with experience, but horizontal wells still cost 15 to 250 percent more than conventional vertical wells [10]. As a compensation for the additional cost, one horizontal well might replace four vertical wells in the same drainage area and tremendously reduce pressure drawdown caused by fluids production as shown in **Figure 7**. In general, horizontal drilling extremely increases production and reduces overall drilling and completion costs.

CONCLUSIONS

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

- Fresh water quality is highly affected by undesigned production rates.
- Minimum well penetration into the fresh water zone should be applied in groundwater aquifers.
- The utilization of horizontal wells provides higher water production at minimal disturbance of water level and formation properties.
- Saline water upconing in aquifers is highly affected by the formation is average permeability and saline water specific gravity and height.
- Aquifer's average permeability and fresh water-saline water interface must be defined precisely.

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Table 1: Major groundwater aquifers in Saudi Arabia [3].

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

Table 2: Technical data for Wasia groundwater used in upconing calculations.

Average permeability (k) = variable (0.5, 1.0 and 1.5 Darcies).
Fresh water zone thickness (h) = 366 m.
Wellbore penetration into fresh water zone (d) = variable with maximum value of 366 m.
Single vertical well drainage radius (r_{ev}) = 423 m.
Single horizontal well drainage radius (r_{eh}) = 846 m.
Length of horizontal well (L) = h, 5h and 7h, m.
Wellbore radius (r_w) = 0.1143 m.
Fresh water viscosity ($?_w$) = 1 cp.
Fresh water specific gravity (g_{w1}) = 1.0.
Salt water specific gravity (g_{w2}) = variable with maximum value of 1.05.
Water formation volume factor ($?_w$) = 1.0.

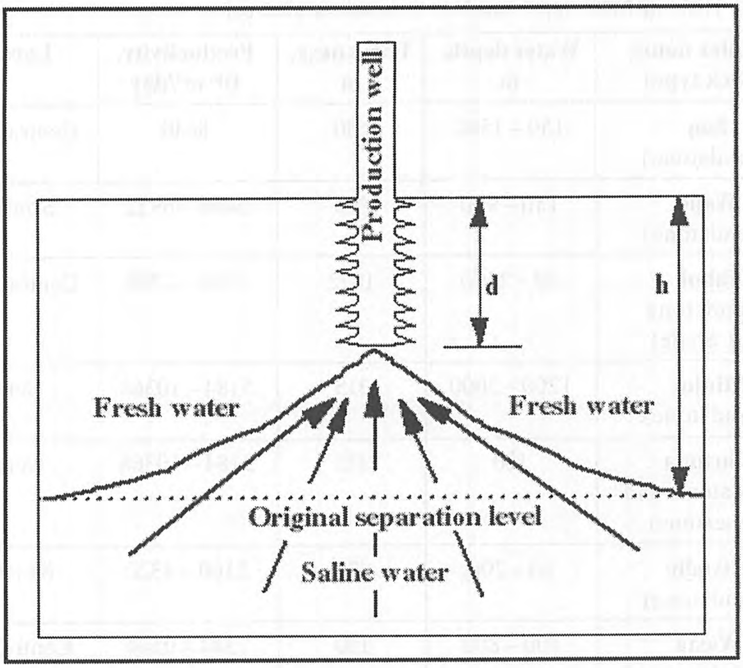

Figure 1 A schematic diagram of upconing phenomenon in a vertical well.

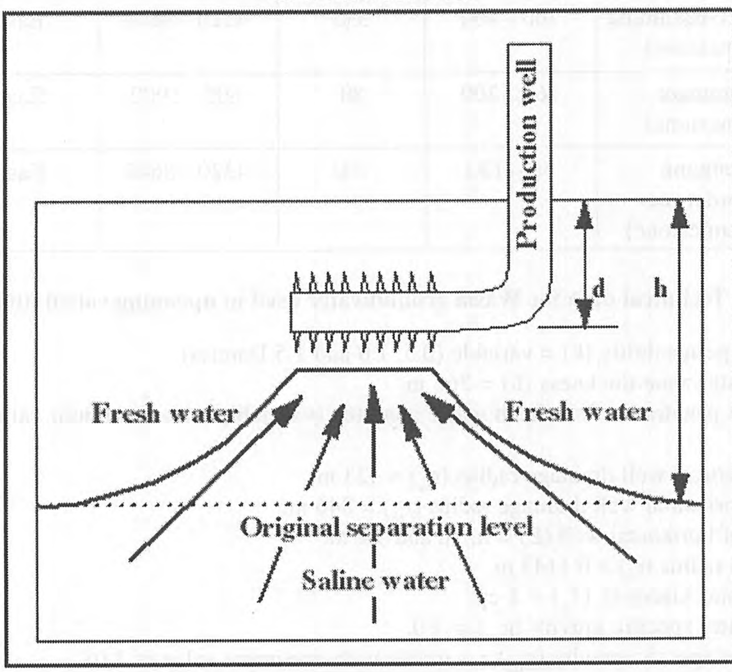

Figure 2 A schematic diagram of upconing phenomenon in a horizontal well.

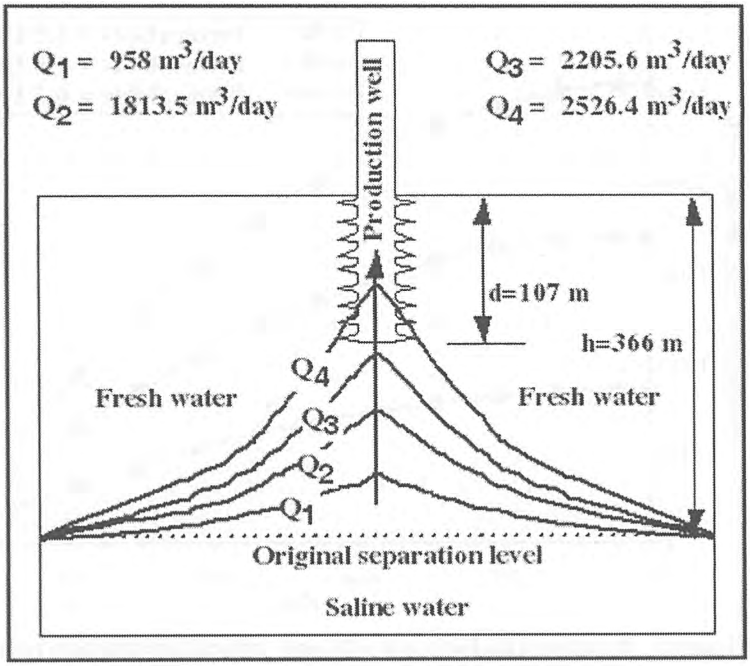

Figure 3 Upconing process example caused by water production in a vertical well in the studied Saudi groundwater aquifer.

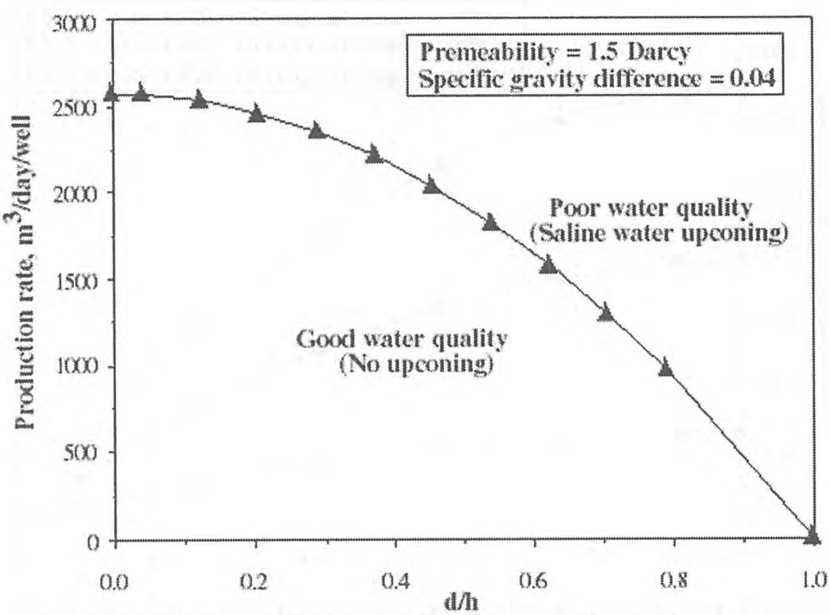

Figure 4 Relationship between d/h and critical production rate from a vertical well in the studied Saudi groundwater aquifer.

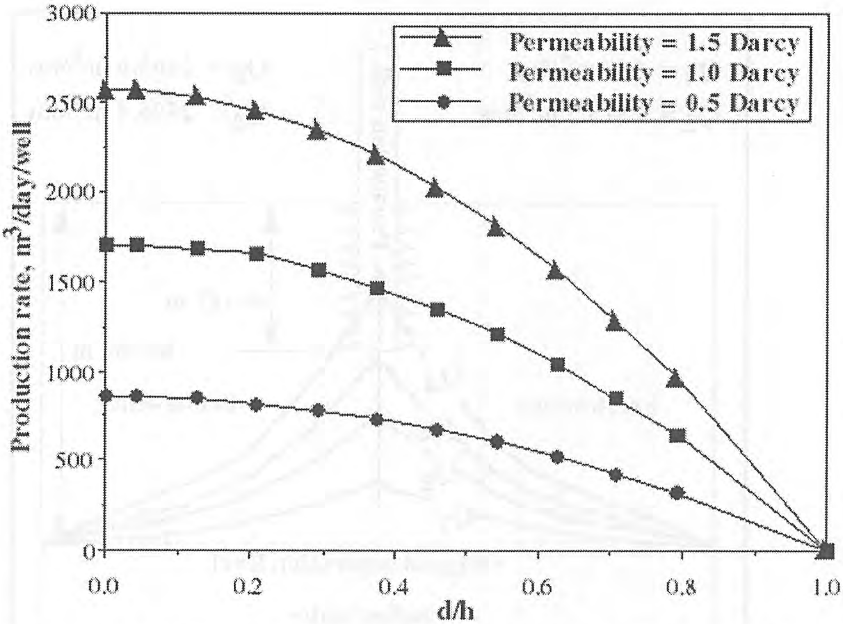

Figure 5 Relationship between d/h and critical production rate from a vertical well in the studied Saudi groundwater aquifer at various permeabilities.

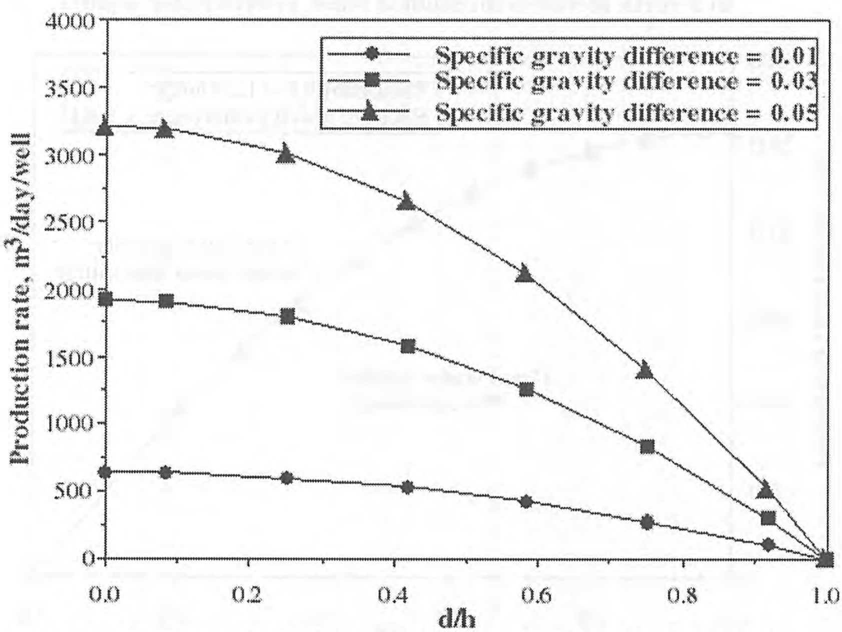

Figure 6 Relationship between d/h and critical production rate from a vertical well in the studied Saudi groundwater aquifer at various specific gravity difference.

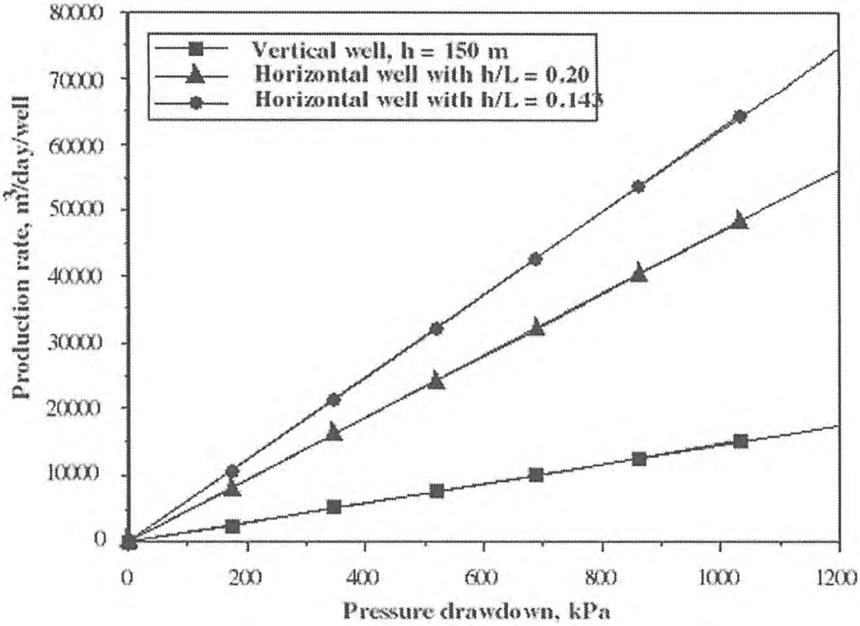

Figure 7 Relationship between pressure drawdown and productio rates from vertical and horizontal wells.

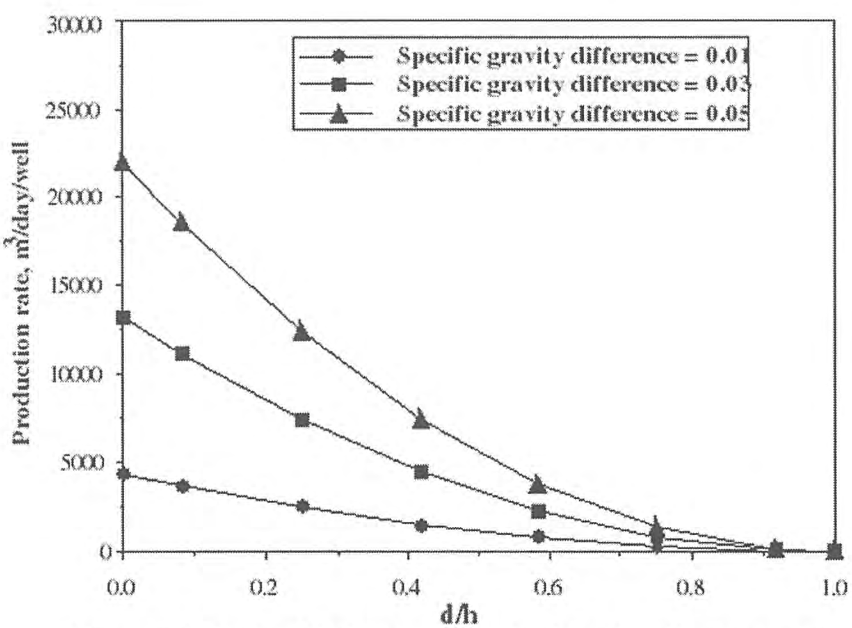

Figure 8 Relationship between d/h and critical production rae from a horizontal well in the studied Saudi groundwater aquifer at various specific gravity difference.

Groundwater Evaluation and Modeling Of East Messan – Iraq

Dhia Yaqub Bashoo and Samaher Lazim

GROUNDWATER EVALUATION AND MODELING OF EAST MESSAN- IRAQ

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ABSTRACT

The studied area is located northeast of Messan province, east of Iraq. The area is 1500 sq. km. It extends beyond the Iraq- Iran borders from the North and Northeast. It lies between latitudes 31ú 50ó- 32ú 27ó North and longitudes 46ú 45ó -,47ú 50ó East. The objectives of the study are to evaluate groundwater resources and extensions of aquifers, estimating their groundwater quality and quantity, and to build up a model simulating the aquifer behavior in the future to avoid the depletion of this valuable resource. Tectonically the greater part of the area lies within the unstable shelf of Mesopotamia. Two major faults exist trending Northwest- Southeast and Northeast-Southwest. Quaternary covers around ninety percent of the area, the rest is covered by Tertiary gravel and conglomerate.The main geomorphological features are Teeb and Dweerege rivers, sand dunes and alluvial fans. The average annual rainfall is 200 mm annual evaporation is 3000 mm. The main aquifers were distinguished in Quaternary and Tertiary. They are confined and unconfined types, the confinement is local. Water balance showed the existence of water surplus, which is 10 mm annually, and about 40% of it percolates to the groundwater. Salinity of water varies between (600- 5000) ppm. The low groundwater salinity is found near the Iranian border in the Tertiary aquifer. The main type of water is Ca- SO_4. The hydraulic head of the aquifer has been investigated through the use of a computer program package. The steady- state natural head distribution prior to the effect of any external stresses have been obtained by the steady- state treatment, and by unsteady- state treatment for a very long simulation period (25 years). Both results gave nearly similar head distribution which is comparable fairly well with measured head values. Results showed reasonable drawdown occurred after one, five, and ten years of pumping.

Introduction

Quantitative and qualitative evaluation of groundwater of East Messan Province is the main aim of this study.

In order to achieve the objectives, the following topics have been investigated.

1. Identification of geological formations, their location, thicknesses, and their extensions.
2. The existence of aquifers, their hydraulic parameters and types.
3. Recharge and discharge of groundwater.
4. The hydrochemical properties of groundwater, its origin and suitability for all purposes.
5. Water surplus.

In addition, a mathematical model is proposed to evaluate the aquifer response to various plans of its exploitation.

Area of Study

The study area is located east of Messan province, south of Iraq, about 1500 sq.km., which extends from the Rushaida region to Al-Teeb and Khuzaina which lies at Iraq-Iran borders, and deeply extends (10- 15) km from the borders. Fig. (1).

The area is a part of the Himreen Hills whose elevation varies between (100 – 250) m above sea level (asl). The area may be considerd as a low relief area which slopes towards the west and southwest reaching an elevation of about 8 m. asl along the Tigris River. Figs. (2, 3, 4, and 5).

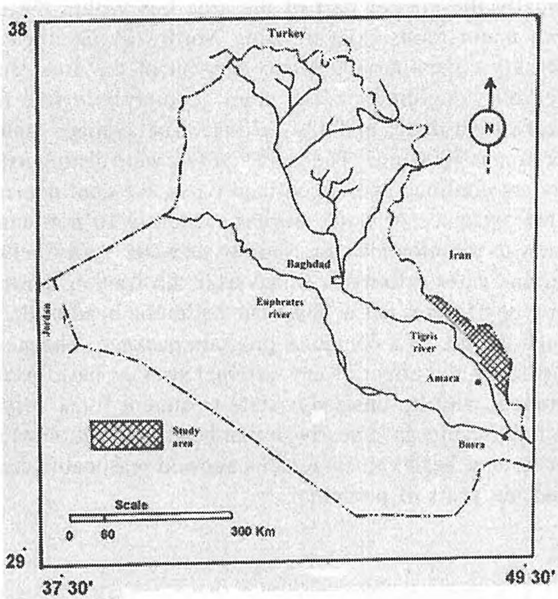

Fig. (1): Location map.

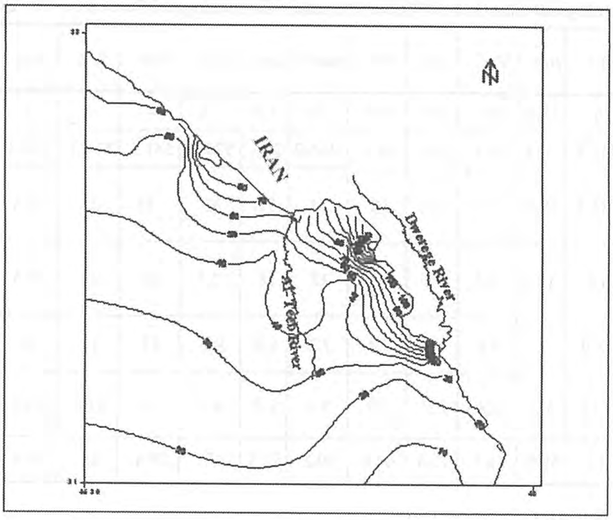

Fig. (2): Topographic map.

Climate

Meteorological elements such as precipitation, evaporation, humidity, and temperature, for more than 20 years, were interpreted to describe the climate condition. Table (1) Interpretation shows:

- Existence of three main periods, wet period, which extend from November to March, dry period summer season, and intermediate period, semiwet (September, October, April, and May) the mean annual rainfall is around (224) mm.

- Measured evaporation by evaporation pan class-A and calculated evaporation by using Linsley(1975)[6] method was conformable and ranged from 2850 to 3300 mm annually

$$E=0.0018\,(25+T)^2\,(100-A) \qquad (1)$$

Where;

E: Monthly evaporation mm

T: Mean monthly temperature Cú

A: Mean monthly relative humidity %

- Mean annual temperature is around 32 C°.
- Aridity index indicates that the area is a semi-arid zone.

Table (1): Meteorological elements of Missan (Amara) Meteorological Station (1980- 2002).

Month / Element	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	march	April	may	June	July	Aug	Mean annual	Total mm.
rainfall	5.1	8	35.6	58	44.1	33.7	29	7.2	3.7	–	–	–	–	224.4
Evap.	350.5	238.8	113	67.8	62.9	94.3	155.2	227	374.4	541.5	552.1	584.4	–	3361.9
Mean max. temp. ^{0}c	41.8	34.4	25.6	18.6	17	19	24	31	38	43	45	44.6	31.8	–
Mean min. temp. ^{0}c	23.3	18	12.7	7.5	6.3	8	12	18	23.3	26	29	27.5	17.6	–
Mean sunrise	10.5	8.9	7	6.2	6.3	7.4	7.3	8.8	9.8	12	11	11	8.85	–
Mean wind speed	4.15	3.18	3.2	2.8	2.8	3.4	3.7	3.9	4.3	6	6.05	5.47	4	–
Mean humidity	29.8	47	52.5	59.5	71.8	64.8	59.2	52.5	36.1	26.4	25	26.8	%47	–

Geology of the area

- The two main tectonic units of Iraq are the shelf unit and the geosynclinal unit. Most of the study area lays within the unstable shelf unit, the Mesopotamian zone, the rest -Northeast -of the area lies within the foothill zone. Fig. (3).
- Geological map Fig. (4), Buday (1980)(2) indicates that the study area is covered by Quaternary deposits (aluvium, fluvail, and Aeolian deposits). Tertiary deposits (mainly Bai- Hassan and Mukdadiyah Formations) are located near the Iraq- Iran borders between Shaikh- Faris and Al- Teeb.

The lithology of these formations is sand, clay, gravel, and conglomerate.

Morphological Features

The main morphological features are:

- Dwerege and Teeb rivers, both originating from Iran, flow into Iraq.
- Sand dunes which represent 15% of the area especially near Manzelia and Khuzaina.
- Alluvial fans that originated from the rivers and their tributary.

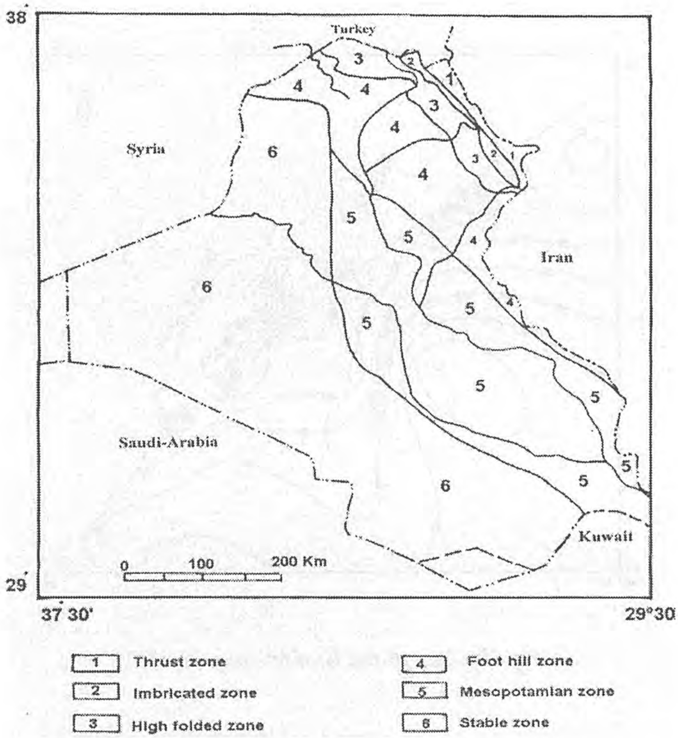

Fig. (3): Tectonic Map of Iraq (after Buday, 1980)[2].

Main aquifers

Several aquifers were penetrated during water wells drilling and they can be summarized as follows:

- Quaternary recent deposits cover almost the entire area; thickness varies between 5 and 40 m.
- Bai- Hassan aquifer, outcrops between Faka and Teeb; thickness varies between 50 and 160 m, decreasing towards Amara town to approximately 5 m.
- Mukdadiyah aquifer, older than Bai- Hassan; thickness reaches around 300 m. near Faka. Bai- Hassan and Mukdadiyah formation are considered as one hydrogeological unit part of a basin which extends to Iran. Figs. (5) and(6).
- Transmissivity of the aquifer varies between (100- 300) m2/ day Fig. (7). The high values are concentrated between Teeb and Dwerege rivers.
- Groundwater flow direction coincides with topography Fig.(8). Density of equipotential line are not similar due to the difference in the transmissivity .
- Outflow rate towards Tigris River according to flow net analysis is around 4000 m3 /day from Northwest region, while from Northeast part it is around 52000 m^3/ day.

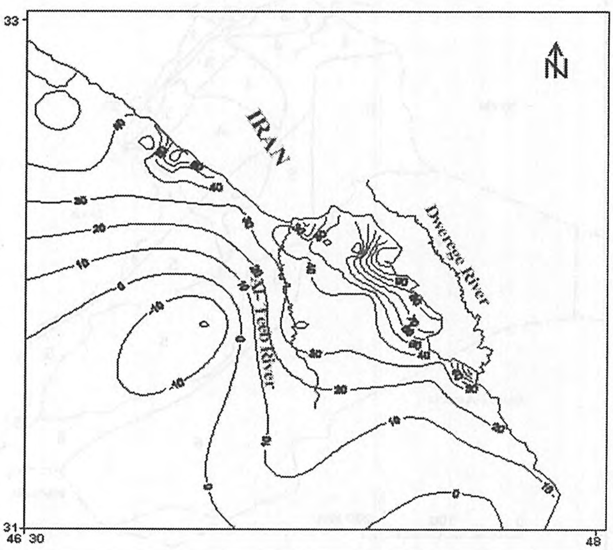

Fig. (5): Top of the Aquifer map (masl).

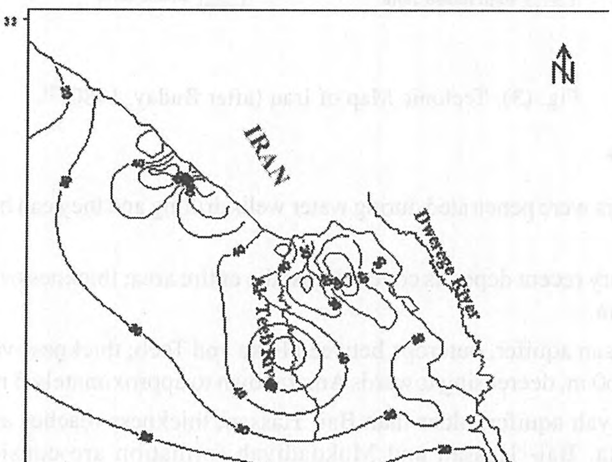

Fig. (6): Thickness of the Aquifer map (masl)

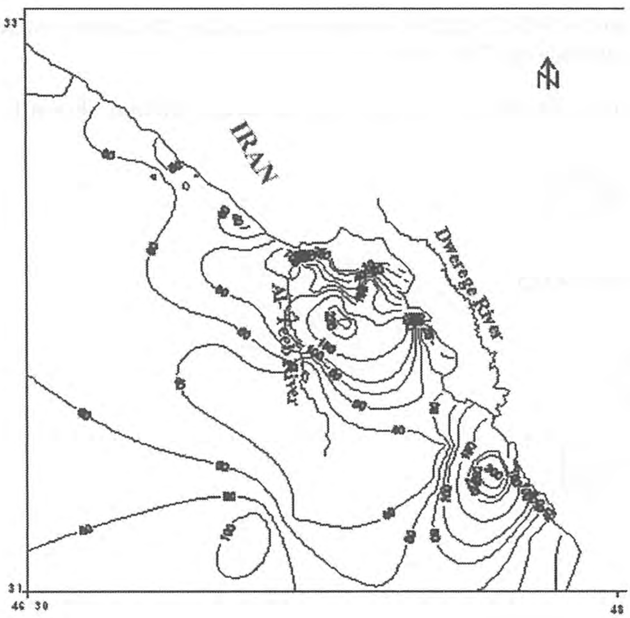

Fig. (7): Aquifer Transmissivity map (m²/d).

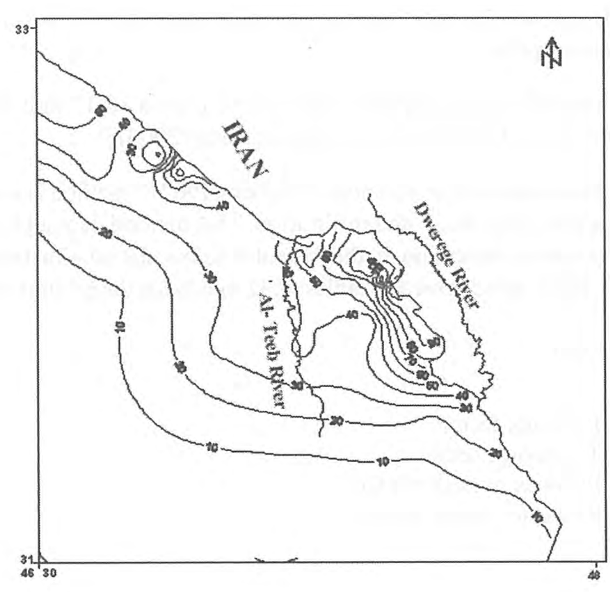

Fig. (8): Flow net map.

Water Balance

The Thornthwait (1948)[3] method is used to calculate the actual evapotranspiration yearly and as average for 20 years.

The main input of Thorntwait formulas are the evaporation as shown below:

$$PE = 16\left(\frac{10t}{J}\right)^{a} \quad (2)$$

$$a = 0.016J + 0.5 \quad (3)$$

$$J = \sum_{J=1}^{J=n} i_j \quad (4)$$

$$i_j = j = \left(\frac{t}{5}\right)^{1.514} \quad (5)$$

Where;

a: constant
t: mean monthly temperature
J: mean annual temperature
PE: potential evapotranspiration

Precipitation, Evaporation, and Evaporanspiration data showed several periods of rainfall and water surplus.

Table (2) indicates that water surplus in the area is around 10.12 mm annually as an average, which is around 4.5 % of the rainfall, Bashoo (2004)[1].

Due to lack of field measurement of runoff, Langbein(1962)[4] method is used to separate the amount of surplus into runoff and infiltration. This method depends on two factors rainfall and temperature. According to the formulas below, the relation between rainfall and runoff (P/ E, R/E), and converting tables, 4.32 mm feeds the groundwater annually.

$$E = 10^{(0.027T+0.886)} \quad (6)$$

Where;

E: Temp. factor
T: Average temp.
P: Mean annual rainfall
R: Mean annual runoff

Table (2): Water Surplus Calculation

Month	Rain fall (mm.)	Evapotran -spiration (mm.)	Corrected Evapotran. (mm.)	Actual Evapotran. (mm.)	Soil humidity (mm.)	Water surplus (mm.)
Sep.	5,1	161,73	159	5,1		
Oct.	8	87,12	85,38	8		
Nov.	35,6	34,37	30,24	30,24	5,36	
Dec.	58	15,02	13,06	13,06	50,3	
Jan.	44,1	8,89	7,91	7,91	86,49	
Feb.	33,7	13,16	11,32	11,32	100	8,87
March	29	27,48	27,75	27,75	100	10,12
April	7,2	72,63	78,44	78,44		
May	3,7	141,96	152,02	152,02		
June	-	206,98	218,8	218,8		
July	-	222,5	277,42	277,42		
Aug.	-	227,83	273,22	273,22		

Qualitative evaluation

- Electrical Conductivity (EC) ranges between less than 1000 ìmohs/ cm to 9000-ìmohs/ cm. Fig. (9). The low values are within the Mukdadiya and Bai- Hassan Formations, i.e. along the international borders.
- High values of EC is due to the slow movement of the groundwater at the discharge area which gives enough time for ionic exchange between the groundwater and the silty sandy clay of Quaternary deposits.
- The main type of water is calcium sulphate, marine origin followed by sodium sulphate type.
- According to the chemical properties and type of water, it can be used for domestic supplies in selected areas, Table (3), if other criteria permit, such as biological, radioactive, organic, and inorganic substances. For irrigation it can be used in areas where the total soluble salts are less than 2000 ppm.

Table (3): Promising Locations for Domestic Supply

Location	T.D.S. (ppm)
Abu- Gharab	450
Chelat	550
Zubaidat	900-800
AL- Sharhani	700
AL- Manzilia	450

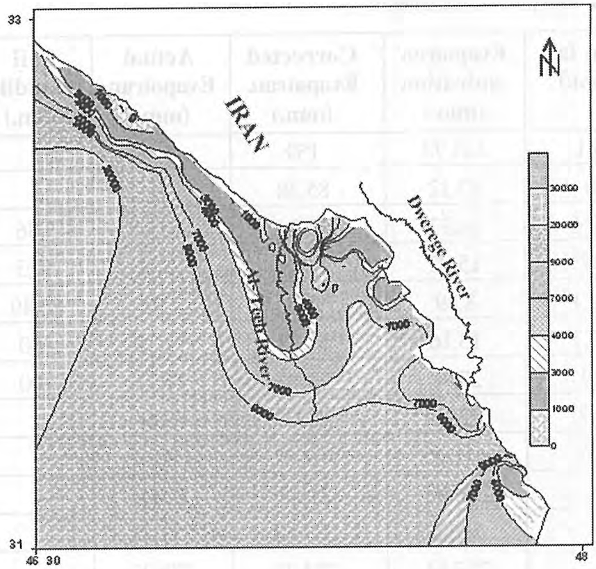

Fig. (9): Electrical Conductivity map (µmohs/cm.).

The Mathematical Model

- In the present work, the MODFLOW of the GMS package (1988)(7) is used to simulate the study area which is about 132.5 km in length and 137.5 km in width, i.e., from the boundary region to the Tigris river. Fig. (10) shows the grid design for the studied area in which the grid system is referenced in terms of row and column. A nonuniform mesh of (71) rows and (66) columns has been designed to simulate the aquifer, with grid dimensions between 1.25 km^2 and 6.25 km^2.

- The northeast boundaries are considered as no flow boundaries as a result of clear topographic divide (Himreen Hills), and some boundaries were considered as constant head like (Dwerege and Tigris) rivers due to lack of detailed data, Lazim (2002)(5).

- A comparison between the contour maps of the observed and computed head values for the steady state conditions Fig. (11), shows some anomalies in the southwest due to the fact that measured head values are not actually representing natural groundwater levels.

- To fulfill the possible future needs for groundwater, 100 new wells were assumed to be installed in the area. It is suggested that each of these wells is producing at a constant rate of a 10 –!/ sec. for 16 hours pumpage based on the amount of water surplus and one meter depth from the static reserve.

- After one year of pumpage, maximum drawdown is 8.2 m. While after five years of pumpage drawdown is 29.2 m. and 44. 8 m after 10 years of pumpage Figs. (12, 13, 17). Results are based on accuracy of input data as transmissivity, storage coefficient,…etc.

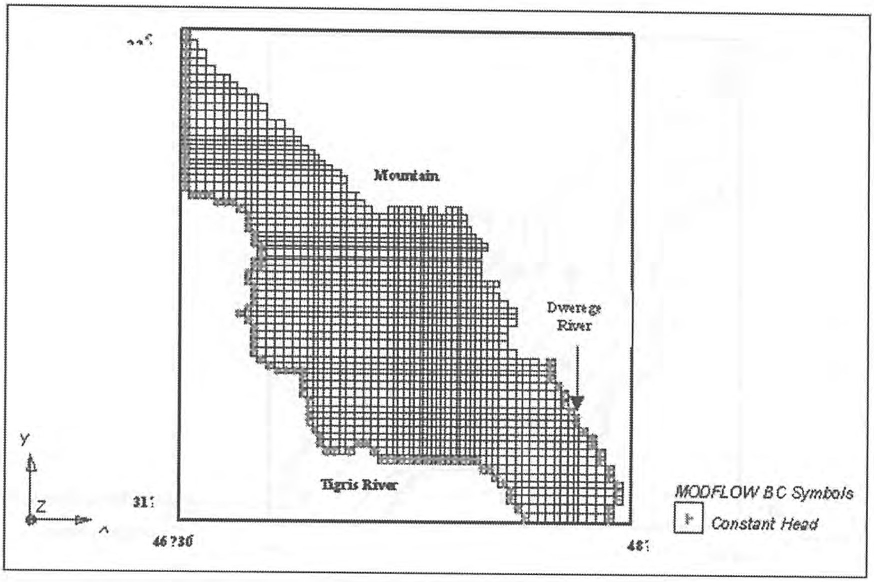

Fig. (10): Grid Design for the Study Area.

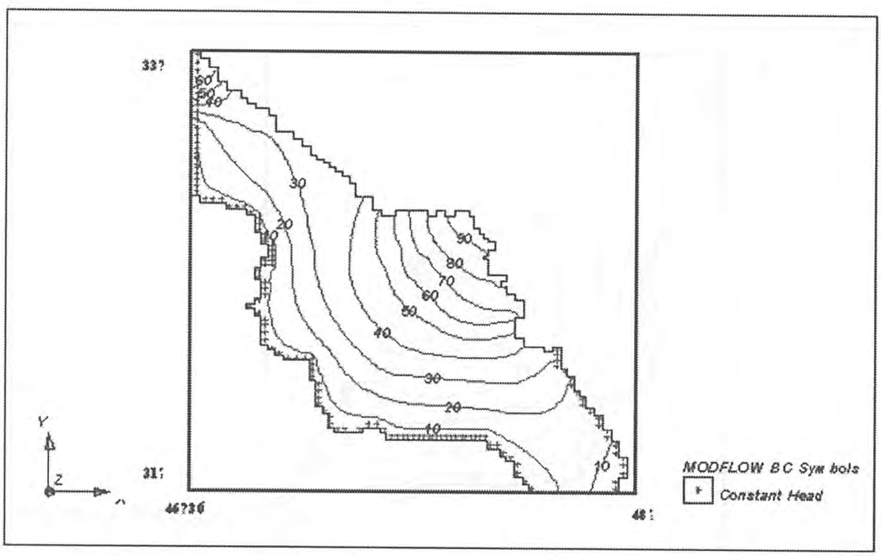

Fig. (11): Steady–State Simulation of the Aquifer.

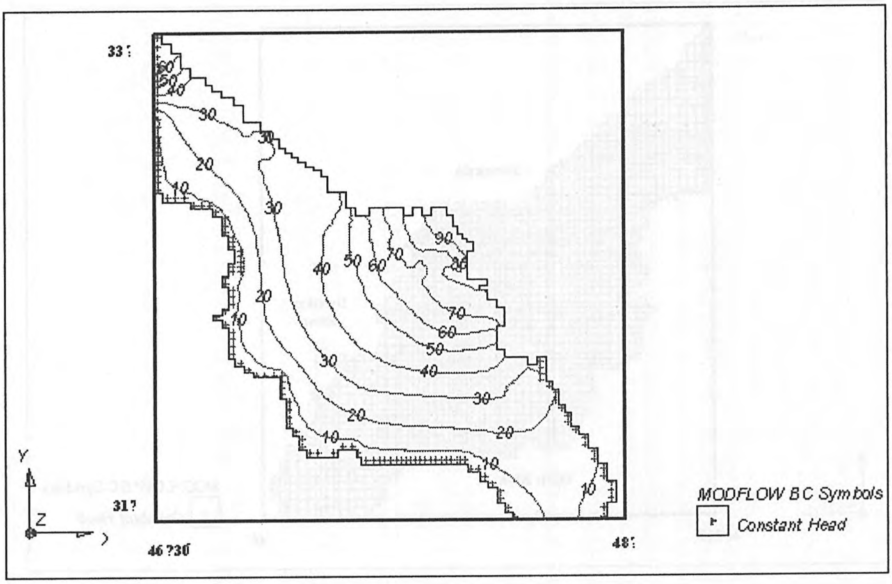

Fig. (12): Water Level Contour Map after One Year Simulation.

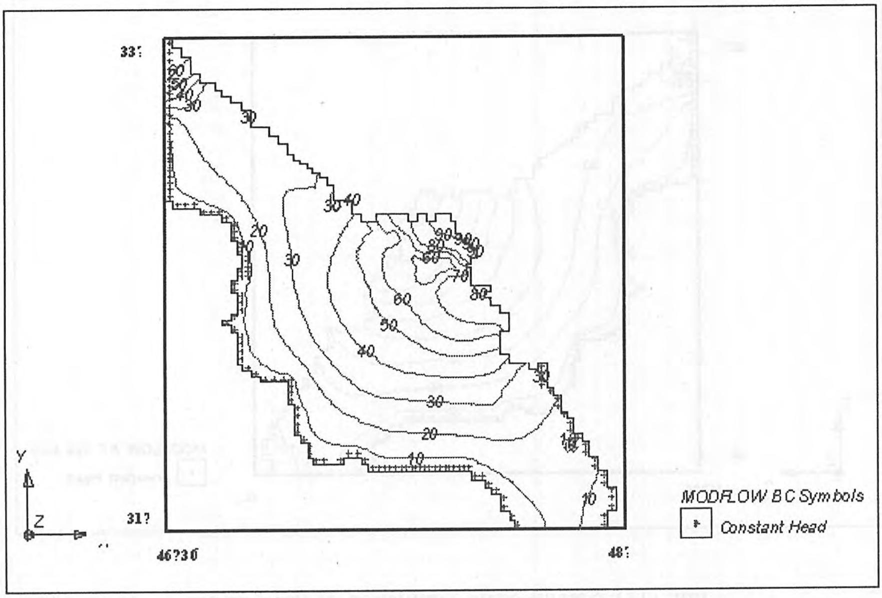

Fig. (13): Water Level Contour Map after Five Years Simulation.

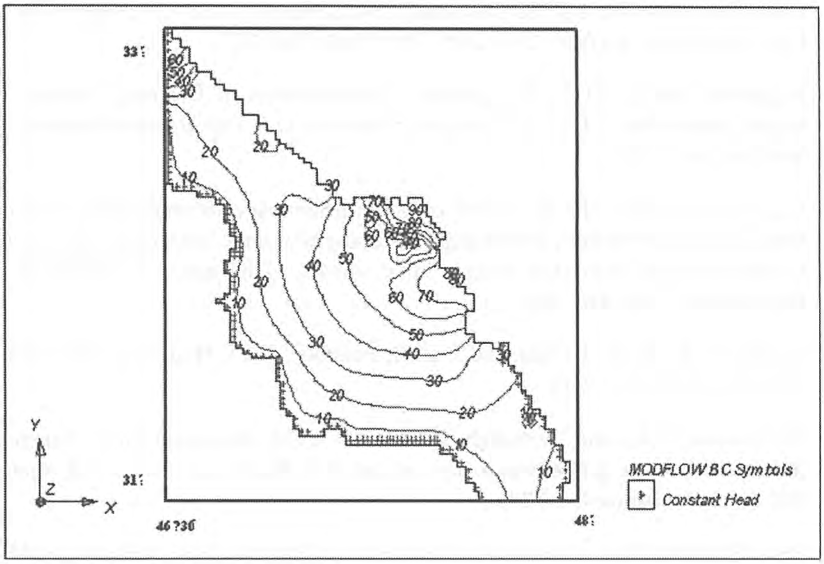

Fig. (14) Water Level Contour Map after Ten Years Simulation.

Conclusions

- Water surplus represents 4.5% of the rainfall, which is around 10 mm.
- The area is simulated by a mathematical model that can be used for prediction of aquifer response for various plans of exploitation.
- The salinity of groundwater increases toward the southwest of the study area as expected because of the slow movement which gives:
    1. Enough time for ionic exchange between the container and the groundwater.
    2. Quaternary deposits contain high saline clay which increases the amount of Ca in the groundwater.
- The prevailing type of water is calcium sulphate. Most of the groundwater is unsuitable for human use except some patches near the border as Abu- Gharab, Jlaat, Zubidat, Sharhani, and Manzlia. For irrigation purposes, the groundwater of the area can be used under certain limitations, i.e., permeable soil with groundwater salinity around 2000 ppm.

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Groundwater balance and flow analysis methods for sub-surface dam in the southwestern islands of Japan

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Hitoshi OUMURA and Teruhiko U SUI

GROUNDWATER BALANCE AND FLOW ANALYSIS METHODS FOR A SUB-SURFACE DAM IN THE SOUTHWESTERN ISLANDS OF JAPAN

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ABSTRACT

It is a critical issue to develop water resources in Japanese remote islands where there are no noticeable rivers. To stabilize and increase agriculture production in these islands, sub-surface dams have drawn considerable attention as a promising approach. Several sub-surface dam projects have been implemented in the southwestern islands. This paper deals with sub-surface dam projects in Japan, and analysis methods of groundwater balance and flow for sub-surface dam planning. First, the paper describes the history, progress, and structure of sub-surface dams including the construction procedure, and then introduces the Miyako irrigation project being evaluated as a remarkable project with a sub-surface dam. Secondly, groundwater balance analysis methods on a planning stage are discussed. To justify available storage capacity and irrigation water requirements, the analysis method called "storage tank model" has been commonly applied to sub-surface dam planning in Japan. An outline of this method and a case study in Okinoerabu-island are described. Finally, the paper discusses simulation methods of groundwater flow for an experimental type sub-surface dam where it is difficult to shut off completely brine invasion from the sea due to deep basement rock along the coast. The effectiveness of two-dimensional FEM (finite element method) analysis by density-dependent flow mass transport was verified through simulating the behavior of brine invasion based on actual pumping-test data of the sub-surface dam experimentally constructed in Tukken-island. In addition to this, the validity of two-dimensional FEM analysis was endorsed by three-dimensional FEM analysis by density-dependent flow mass transport.

Keywords: sub-surface dam, groundwater analysis, storage tank model, two-dimensional FEM analysis, three-dimensional FEM analysis

I Introduction

Since the first sub-surface dam Kabashima-dam was completed in 1973, more than ten sub-surface dams have been constructed in Japan. Most of these dams are located in the southwestern islands around 1,500 km southwestward of Tokyo as shown in Figure 1.

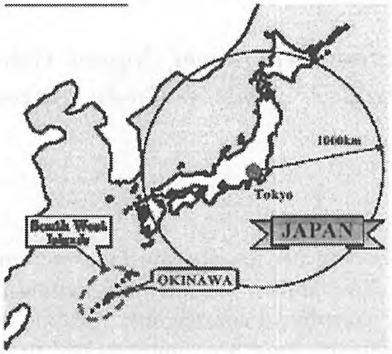

Figure 1: Location map of the southwestern islands

In this paper, the history, progress, structure, and construction procedure of the sub-surface dam are described, and the analysis method for groundwater balance called the storage tank model and the simulation method for groundwater flow, the two-dimensional FEM analysis method and the three-dimensional FEM analysis method are discussed.

II Sub-surface dam project in southwestern islands, Japan

II-1 Natural condition of southwestern islands

Although the southwestern islands in and around the Okinawa main-island receive plentiful annual precipitation of about 2,000 mm, the distribution of rainfall fluctuates depending on the year and season. Most of the rainfall concentrates in typhoon and tropical cyclone seasons; therefore, farmers have frequently suffered damages from heavy rainfall, strong wind during typhoons, and/or a long spell of drought. According to the records of the Okinawa meteorological station a drought is observed every four years.

For realizing stable agricultural production in the southwestern islands, water resources development is recognized to be the most important issue. However, a suitable site for a surface storage dam is limited due to the flat topography and the permeable geological features. Most of the rainfall immediately infiltrates into the underground dominated with porous Ryukyu limestone and flows out to the surrounding sea as illustrated in Figure 2. Accordingly, it has seemed to be difficult to utilize groundwater in southwestern islands.

To overcome these situations, a sub-surface dam was proposed as a promising approach, which prevents groundwater from flowing out to the sea and stores it in the underground as shown in Figure 3.

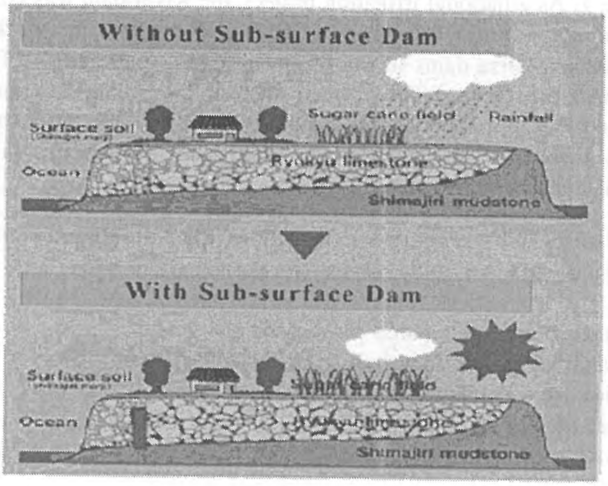

Figure 2: Concept diagram of sub-surface dams

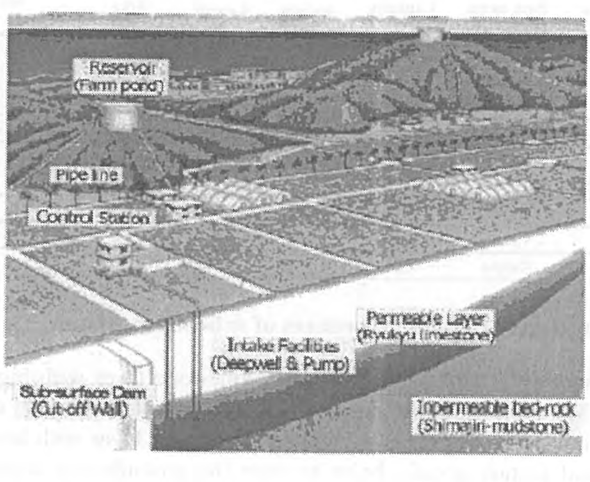

Figure 3: Overview of irrigation system with a sub-surface dam

II-2 History and progress of sub-surface dam

The Kabashima-dam is the first sub-surface dam, completed in 1973 for drinking water purposes with a storage capacity of 9,000 m^3 in Kabashima-island of Nagasaki Prefecture. The second is the middle-scale Minafuku-dam with a storage capacity of 700,000 m^3, which was experimentally constructed in the Miyako-island of Okinawa Prefecture in 1979. Since then, the Tunekami-dam (1985), the Miko-dam (1996), and several other sub-surface dams have been constructed in Japanese islands.

The Sunagawa-dam and the Fukuzato-dam in the Miyako-island opened up the way for an irrigation project with a sub-surface dam in the southwestern islands, following these several sub-surface dam projects were launched in the southwestern islands as shown in Table 1. As a national irrigation project, the Kikai-dam was completed in the Kikai-island of Kagoshima Prefecture in 2001, and construction works of the sub-surface Komesu and Giiza-dams in the Okinawa main-island and the Thihara-dam in the Izena-island are on going. The projects such as the Yokatu-dam in the Okinawa main-island and the Kanjin-dam in Kume-island have been implemented as the Okinawa Prefecture Government project. In addition, planning for other projects in Okinoerabu-island and Ie-island are in progress.

It can be said that such great strides depend on the following advantages of sub-surface dams in comparison with surface storage dams:

1) Stable water supply is ensured throughout the year.
2) Present land use is not disturbed.
3) Evaporation from the dam is negligible.
4) High water quality can be kept.
5) Compensation cost for the resettlement of inhabitants and residences is low.

Table 1: List of irrigation projects with sub-surface dams

Project name	Dam name	Storage Capacity ($1,000m^3$)	Dam body		Irrigation Area (ha)	Progress
			Height (m)	Length (m)		
Miyako	Minafuku	700	16.5	500	8,160	'1979 Completion
	Sunagawa	9,500	50	1,677		'1994 Completion
	Fukuzato	10,500	27	2,908		'1998 Completion
Kikai	Kikai	1,800	35	2,280	1,700	'2001Completion
Okinawa Honto nanbu	Komesu	3,460	69.4	2,489	1,350	On going
	Giiza	390	53	969		
Izena	Senbaru	80	-	550	520	On going
Yokatu	Yokatu	3,963	67.6	705	225	On going
Kume	Kanjin	1,580	57.6	1,088		On going

II-3 Structure and construction procedures of sub-surface dams

In most of the southwestern islands, a Ryukyu limestone layer with high permeability (in case of the Miyako-island, the permeability coefficient is 3.5×10^{-1} cm/sec and the available void ratio is 10%) covers a Shimajiri mudstone layer with low permeability. Such a geological feature greatly helps to store the groundwater underground.

A sub-surface dam is characterized by a cut-off wall that shuts off and dams up flowing groundwater, and stores groundwater inside the porous Ryukyu limestone layer. In some cases, the prevention of brine invasion is required as an additional function for the cut-off wall.

The continuous cut-off wall method or grouting method has been applied to the construction of the cut-off wall. The former is an in-situ churning method which constructs a continuous concrete wall under the ground, using the excavated and crushed limestone as aggregate mixed with cement at the site. The latter is a traditional method; the boring machine makes holes in the ground surface and then injects cement milk with proper pressure to fill up the void surrounding the boreholes. Figure 4 [1] shows the construction procedure of the continuous cut-off wall from the preparatory work to in-situ churning. In the case of the Miyako-islands, an impermeable cut-off wall (permeability coefficient is less than 1.0×10^{-6} cm/sec) with around 50 cm in width, penetrates around one meter in depth into the basement mudstone.

II-4 Irrigation project with a sub-surface dam

A typical irrigation system with a sub-surface dam is illustrated in Figure 3. Irrigation water stored in the underground is lifted up by submergible motor pumps to the reservoirs given with enough elevation for the benefited area, and then it is distributed by gravity to the farmlands equipped with sprinklers and/or drip tubes through pipeline network.

The Miyako irrigation project drastically changed prevailing rain-fed farming to profitable agriculture targeting cash crops such as tropical fruits and vegetables. A project with farmlands of 8,160 ha and beneficiaries of 5,685 households was implemented in collaboration with The Ministry of Agriculture, Forestry and Fisheries, Japan the Green Resources Corporation, and the Okinawa Prefecture Government. An advanced irrigation system consisting of two sub-surface dams, pump equipments, reservoirs, and pipeline networks, was established by this project, which spent a period of 14 years and a total cost of 64 billion yen (equivalent about $60 million).

171 submergible motor pumps (D = 125 mm) with a capacity of 2,000 m^3/day/pump (1.383 m3/min/pump) were equipped for the drilled tube wells. The distribution of irrigation water is controlled by 18 pumping stations each is composed of 8 to 11 submergible motor pumps.

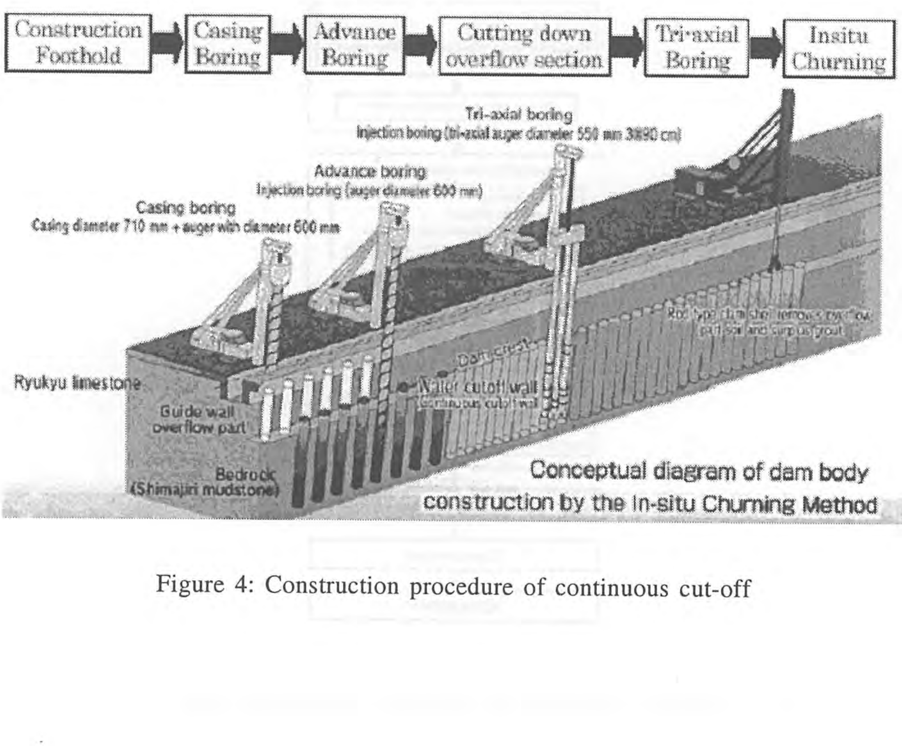

Figure 4: Construction procedure of continuous cut-off

III Analysis method of groundwater balance for sub-surface dam planning

III-1 Selection of groundwater analysis methods

The planning procedure for a sub-surface dam is divided into five stages, namely: basic survey, investigation and planning, detail design, construction, and management as shown in Figure 5 [2].

A basic survey is conducted in order to find candidate sites for the sub-surface dam. As the first step of this stage, outline of geographic features as well as hydraulic and hydrologic conditions should be grasped from a technical viewpoint. Besides, a socio-economic survey must be carried out to collect the information on water demand for agriculture and other purposes, present land use as well as water rights, related laws, and regulations relating to both surface water and groundwater. Several candidate sites for the sub-surface dam are proposed based on the survey results.

At the investigation and planning stage, geographic features, physical characteristics of strata, and hydrologic characteristics of aquifer at each candidate site are examined in detail to finalize the sub-surface dam site. Comprehensive groundwater balance analysis is made to fix available dam storage capacity and irrigation water requirement. The simulation model, which expresses actual hydrologic situation, is formulated. Then, the proposed height and length of the cut-off wall and storage capacity of the sub-surface dam is estimated using the groundwater balance analysis.

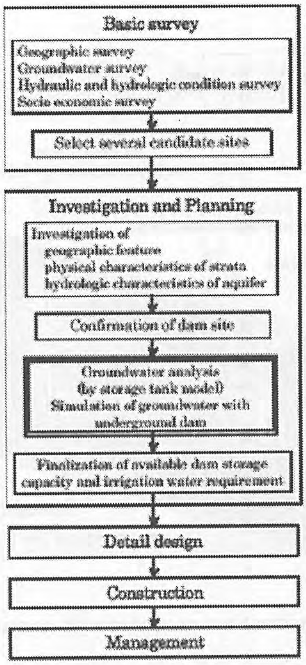

Figure 5: Planning procedure for sub-surface dams

Several methods such as storage tank models, difference models, finite element methods and boundary element methods have been proposed so far. Storage tank models have been widely applied to sub-surface dam planning in Japan since this method satisfies the following requirements for groundwater balance analysis: [3] [4]

- Quantitative fluctuation of groundwater level can be traced.
- Fluctuation of groundwater amount can be simulated on a time series base.
- An analysis model can be easily formulated in accordance with each dimension.
- Simulation for long periods over 30 years long can be executed in a short time.

III-2 Outline of storage tank model

Some part of rainfall is lost as surface drainage and evaporation, the remaining infiltrates into the underground. Infiltrated groundwater is classified into two types of water flow, one is groundwater flow in unsaturated stratum that vertically goes down to the groundwater table, and the other is groundwater flow in saturated stratum that horizontally moves as groundwater flow.

In storage tank models, groundwater flow in unsaturated stratum is expressed by ground surface tanks and groundwater flow in saturated stratum is expressed by an underground tank. The principle of storage tank models is summarized below and its concept is illustrated in Figure 6.

- Storage area is divided into multiple blocks which are expressed by ground surface tanks and underground tanks.
- Ground surface tank controls the amount of drainage on ground surface and filtration towards the underground by means of adjusting arrangement and size of filtration holes.
- Underground tank controls the amount of storage underground and the side flow toward the adjoining tank.

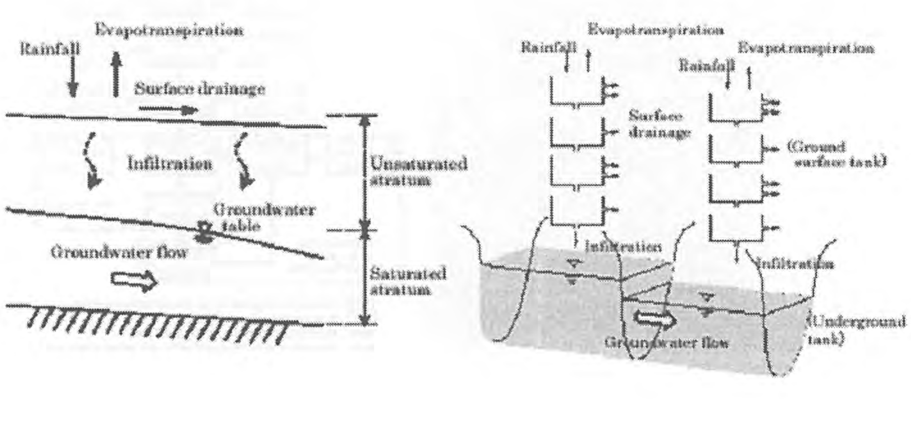

Figure 6: Image of storage tank model

III-3 Case study in the Okinoerabu-island

Practical groundwater analysis using storage tank models is discussed in this paragraph. The Okinoirabu-island is a remote island with a total area of about 100 km^2 located around 200 km north of the Okinawa main-island. Porous Ryukyu limestone is widely observed beneath the ground surface, and doline and gaps spread over the ground surface. Under such a present condition, most of the rainfall infiltrates underground and is then drained as groundwater flow or spring flow to the river. In order to ensure a stable irrigation water supply, a sub-surface dam is proposed for the farmlands of about 1,700 ha where sugarcane, flower, vegetable, and tobacco etc, have been cultivated.

Based on the geological review, depressed valley formulates main aquifer at the upstream of the proposed sub-surface dam basin. The basin is divided into 16 blocks as shown in Figure 7. Both ground surface tanks and underground tanks are shared by BLOCKs 1 to 8 because these areas formulate the main aquifer zone. Among them, the storage zone is represented by BLOCK 6-1 and BLOCK 6-2. Ground surface tanks are shared by BLOCKs 9 to 16 because there is not enough aquifer. Water balance in the actual situation was simulated with a storage tank model assuming that the available void ratio is 7.5 to 8. % and the permeability coefficient is 1.5×10^{-2} cm/sec according to the result of soil physical analysis and a pumping-test.

Justification of this model was made by using the groundwater level data recorded for three years from 2001 to 2003 at six groundwater observation holes drilled in the aquifer blocks. Table 2 shows the mean absolute error (difference) between the recorded water level and the calculated water level on a yearly base. It was confirmed that the average absolute error for three years is kept within the range less than 1.0 m at every observation hole. This result leads to the conclusion that this model expresses the actual situation with high accuracy.

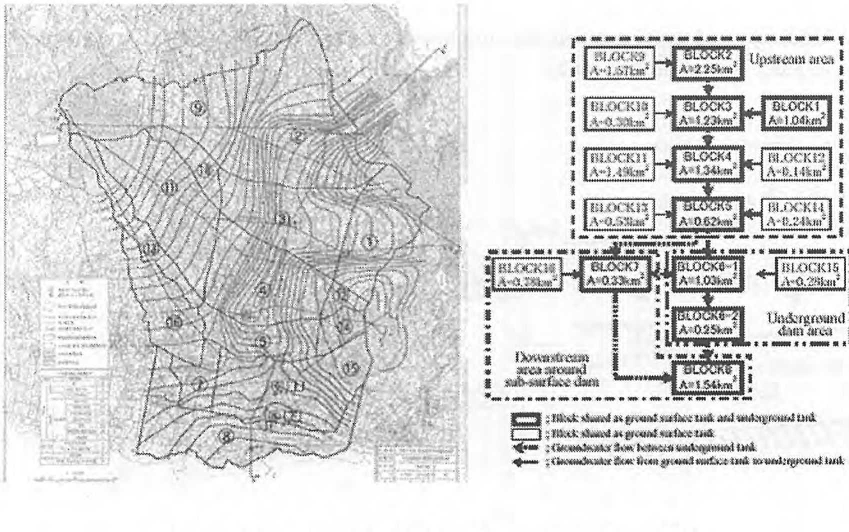

Figure 7: Basin and blocks of storage tank model

Table 2: Mean absolute error between the recorded water level and the calculated water level (m)

	BLOCK3	BLOCK 4	BLOCK 5	BLOCK 6-1	BLOCK 6-2	BLOCK 8
2001	-	1.161	-	1.242	0.608	0.332
2002	-	0.251	-	0.943	0.403	0.354
2003	0.337	0.317	0.358	0.407	0.310	0.190
Average	**0.337**	**0.576**	**0.358**	**0.964**	**0.440**	**0.292**

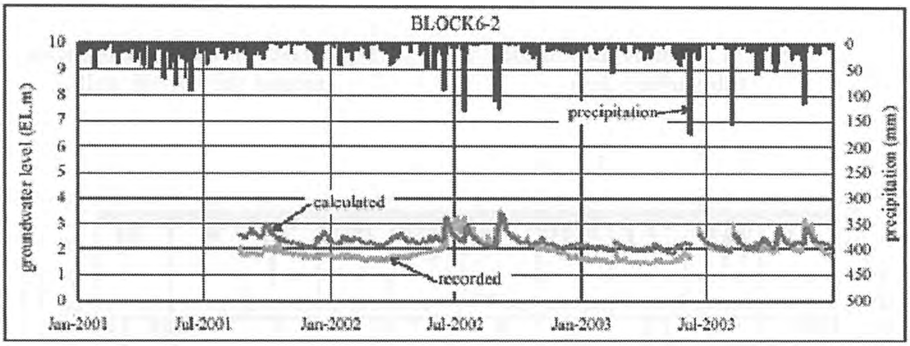

Figure 8: Simulation result at BLOCK 6-2

III-4 Groundwater simulation with sub-surface dam in Okinoerabu-island

Groundwater simulation was made for the period of 30 years from 1973 to 2003 with a storage tank model formulated in the previous paragraph for the case that groundwater stored in the sub-surface dam is lifted up by submergible motor pumps. Figure 9 indicates an alignment of the proposed dam axis. Overflow from the crest, seepage through the cut-off wall, and filtration through the basement rock is drawn in Figure 10. The calculation was executed assuming that the crest of the cut-off wall is 19 m above sea level (EL=19 m) and the penetration in basement rock is one meter in depth. Each discharge is obtained by the water level difference between a storage block and a downstream block, and the permeability coefficient (k 1.0×10^{-7} cm/sec) of the cut-off wall.

Figure 11 shows the fluctuation of the groundwater level with and without a sub-surface dam based on the simulation result of BLOCK 6-2 for the period of 10 years from 1993 to 2003. The groundwater level is kept low around 3m above sea level without a sub-surface dam. In contrast, the water level rises up to full water level (EL=19 m) with a sub-surface dam, and it falls to nearly 0 m during pumping.

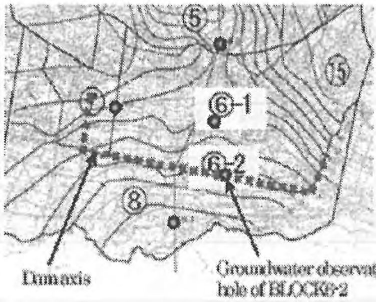

Figure 9: Location map of the sub-surface dam

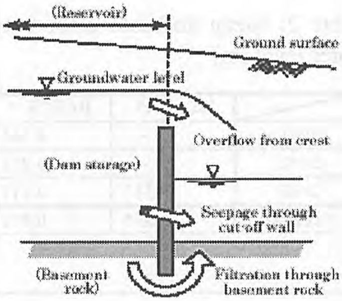

Figure 10: Groundwater behavior around the cut-off wall

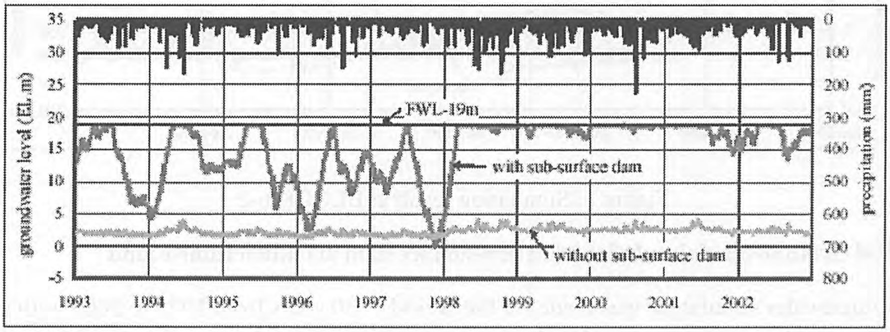

Figure 11: Simulation results of BLOCK 6-2 with and without a sub-surface dam

IV Three-dimensional analysis method on groundwater flow and brine invasion

V-1 Sub-surface dam type and analysis method

In the previous section, the paper described a standard sub-surface dam type that completely shuts off brine invasion using a continuous cut-off wall, namely it dealt with the analysis method focusing on fresh water.

In this section, the paper discusses the analysis methods for an experimental type of sub-surface dams, which shuts off brine invasion with difficulty because the basement rock is laid so deep. To gather technical information on this type, a sub-surface dam was experimentally constructed in the Tukken-island (see Figure 12) located around 5 km south-southeast of the Katuren Peninsula in the Okinawa main-island. A possibility of storing fresh water and the behavior of the invading brine during pumping are examined through the comparison of the data recorded at the actual site the result were obtained by a numerical computation.

An interface model was adopted to analyze simultaneously the behaviors of salt water and fresh water, premising that its interface's electric conductivity is 20,000 ìs/cm as shown in Figure 13. However, this analysis model can not be applied to the use of irrigation water because the brine density of irrigation water should be kept less than 2,000 ìs/cm.

Accordingly, the finite element method (FEM) by density-dependent flow mass transport was recommended for the groundwater flow analysis targeting the use of irrigation water.

IV-2 Case study in Tukken-island

(1) Two-dimensional FEM analysis by density-dependent flow mass transport

The amount of fresh water recharge is estimated by a storage tank model, the proposed basin area (1,200 m × 1,000 m) is divided into 13 blocks as shown in Figure 14. In order to confirm the possibility of storing fresh water and simulate the behavior of brine caused by pumping at the intake well, FEM analysis by density-dependent flow mass transport was made on a time series base at the section including the continuous cut-off wall as illustrated in Figure 15 and Figure 16.

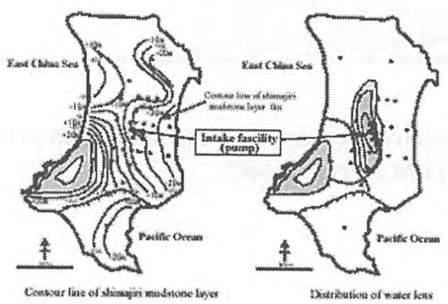

Figure 12: Foundation contour line and fresh water lens in the Tukenjima-iland

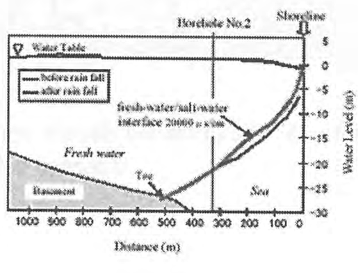

Figure 13: Fresh-water/salt-water interface model

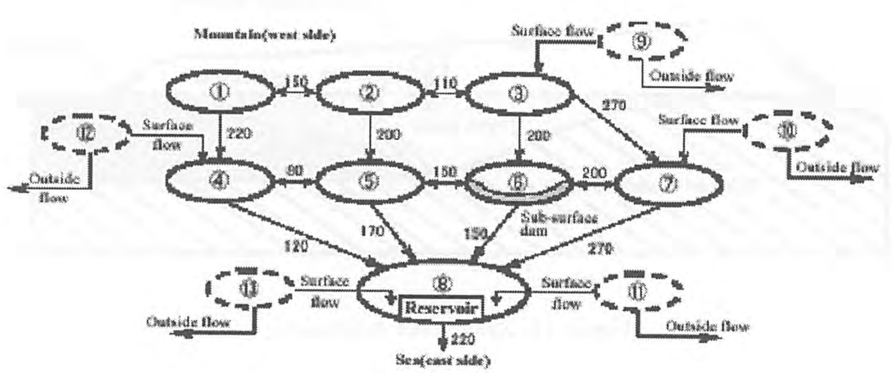

Figure 14: Schematic diagram of storage tank model

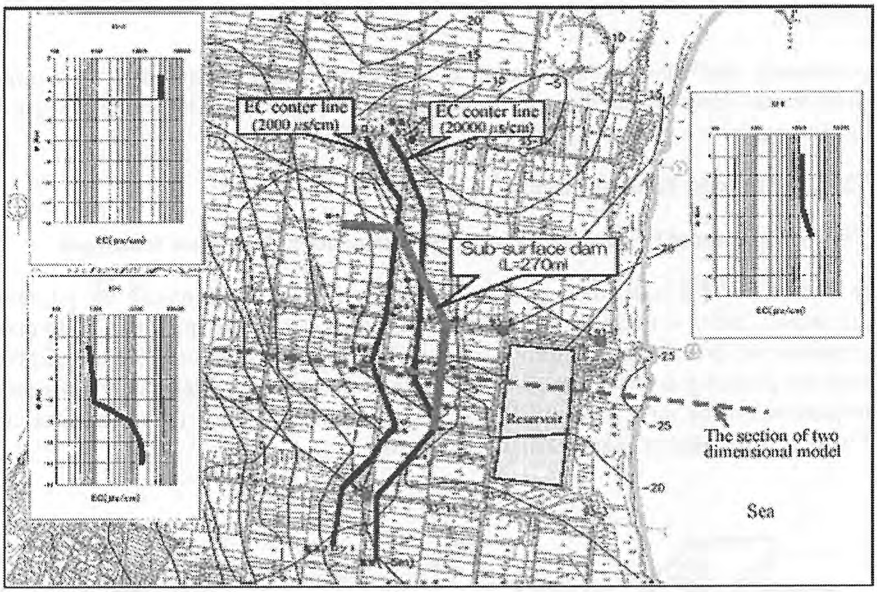

Figure 15: The observed electric conductivity contour line and the section of two-dimensional FEM analysis model

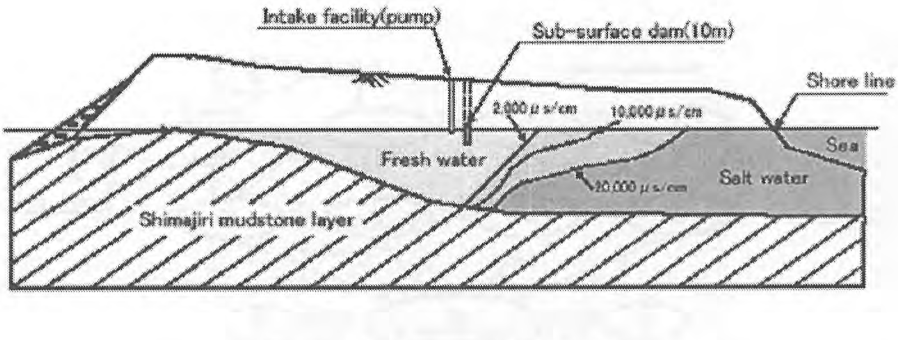

Figure 16: Salty water distribution

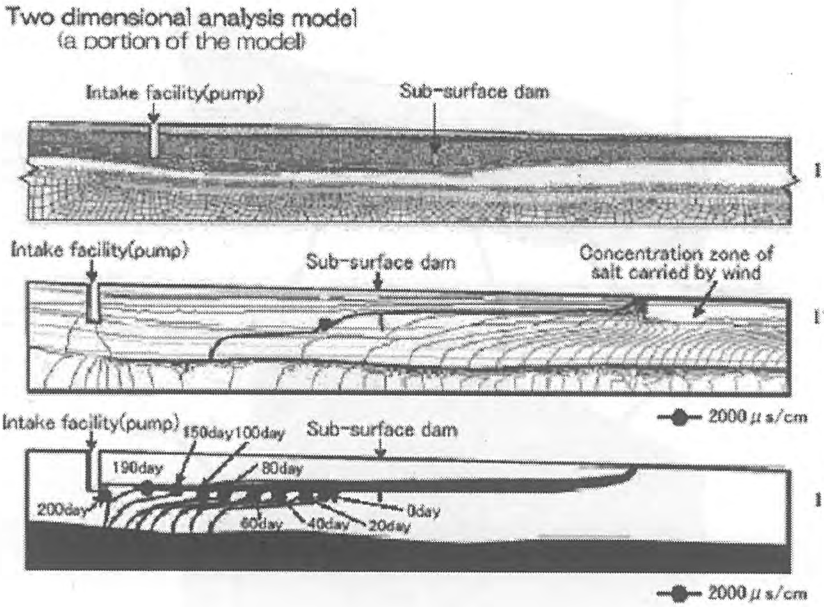

Figure 17: Result of two-dimensional FEM analysis by density-dependent flow mass transport

Figure 17a shows the two-dimensional FEM analysis model consisting of 30,943 elements and 30,469 points. The computation result indicates that the fresh water zone expands through incomplete shutting by the cut-off wall and that the distribution of brine density meets the data measured at the observation holes as shown in Figure 17b. Figure 17c shows that the density line of 2,000 ìs/cm reaches the intake well after 200 days of continuous pumping at the rate of 800 m^3/day. It means that groundwater can be utilized continuously for irrigation within 200 days in the case of the pumping rates mentioned above.

(2) Three-dimensional FEM analysis by density-dependent flow mass transport

For preparing the management program of pump operation and optimizing the placement of intake wells, it is needed to clarify the details of brine invasion around the continuous cut-off wall and the brine entrapment due to the intake of groundwater. To simulate such phenomena in detail, three-dimensional FEM analysis method by density dependent flow mass transport is proposed. [5][6][7][8]. Figure 18 demonstrates a brine density contour line showing the shape of water lens formed by the cut-off wall and the situation of brine invading from the coastline.

Through the case study of the Tukkenn-island, it can be said that the validity of the two-dimensional FEM analysis was endorsed by three-dimensional FEM analysis.

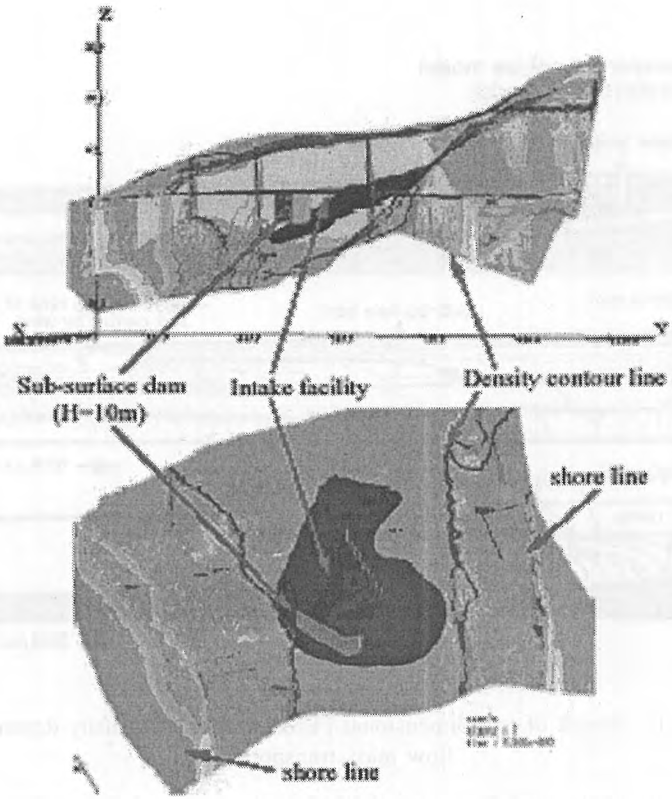

Figure-18 Result of three-dimensional FEM analysis by density-dependent flow mass transport

V Conclusion

This paper described the experiences of sub-surface dam projects, groundwater balance analysis methods for planning a sub-surface dam, and groundwater flow simulation including brine invasion. Irrigation projects with sub-surface dams achieved successful results in the southwestern islands of Japan; therefore, sub-surface dams have drawn considerable attention as an innovative approach in the area where it is difficult to develop water resources in traditional way.

Likewise, sub-surface dams are recognized to be a very effective approach for water resources exploitation in the Gulf arid area characterized by rainfall scarcity and a high evaporation rate. That is why the application of sub-surface dams has been examined in some Gulf countries.

VI Acknowledgments

Finally, we would like to extend our appreciation to the Director General Zahir Khalid Al-Suleimani from the Water Resources Affairs of The Sultanate of Oman and the

organizers of the Seventh Gulf Water Conference for giving a chance to explain groundwater analysis methods on sub-surface dam planning in Japan. We expect that this paper will be of value for the advancement of water resources development in Gulf countries.

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Microbial assessment of groundwater

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MICROBIAL ASSESSMENT OF GROUND WATER

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ABSTRACT

The incidences of waterborne diseases are increasing rapidly at an alarming rate in Pakistan due to unhygienic sanitation. Especially large metropolitan cities are falling into its prey. This study shows that about 25 percent of all the illnesses in Lahore are due to severe cases of waterborne diseases. The poor sanitation system is the root cause for this scenario. Potable water samples were collected from different sites of the city. They were classified mainly as samples from the groundwater source, i.e. municipal tube wells, domestic bore holes and samples from the distribution system. Most of the samples collected from the deep municipal tube wells (about 750 feet deep) were free from coliform bacteria (pollution indicator bacteria found in the intestines of warm blooded animals), but ironically the samples from the domestic boreholes (about 250 feet depth) and samples from distribution system were contaminated with coliform and e-coliform. The samples from the distribution system serving slums were much more contaminated, probably due to non-chlorination of the water as compared to the water which is regularly chlorinated in posh areas of the city. On investigation it was found that there are several reasons for the contamination of groundwater and water in the distribution system. As in the case of groundwater, it is evident that intensive usage of soakage pits has caused major pollution in the groundwater at shallow depths. While leakage of main sewers and open wastewater drains are contributing their share in contamination of ground water, usage of galvanized iron material (which deteriorates rapidly under moist condition) as service pipe for the water supply system is one of the reasons for the contamination of distribution system. When these pipes are laid along and/or inside the wastewater drains, contamination of the water supply occurs. Laboratory results show that water distribution in underdeveloped areas of the city is highly contaminated and ground water available at lower depths is also infected by microbial activities. Data collected from the different hospitals shows that waterborne diseases vary their trend seasonally. In the rainy season, the waterborne diseases graph approaches maximum which indicates that contamination of ground water and water supply distribution systems are mostly infected during this season. This situation can be dealt with by improving the hygienic and sanitation system in the city. Selection of an appropriate technology for sanitation is an important consideration. When considering sanitation options, the aim should be to break the waterborne disease cycles. Onsite sanitation should be avoided as far as possible, other wise the septic tank and soakage pit should be lined properly and there should be at least 3 m thick soil layer between the bottom of soakage pit/septic tank and groundwater table in the wet season. Also, if a hand pump for water is being used by the dweller, then there must be at least 7 m of horizontal distance between pit and the well. Chlorination of drinking water before distribution at municipal tube wells and proper periodic cleaning of individual water tanks should be encouraged. Proper sanitation and water supply systems are essential to control the influence of waterborne diseases within the city.

Keywords: Coliform, E-coliform (E-coli), soakage pit, leachate, waterborne diseases, fecal contamination

Introduction

The provision of safe drinking water supplies and proper sanitation are accepted as key elements for the improvement of health in many developing countries. As resources are rarely adequate enough to provide piped water supplies and sewerage systems universally, the most cost effective solution is often to construct low yielding boreholes and onsite sanitation with proper care. However, there are serious concerns that onsite sanitation may contaminate nearby wells and springs [1].

The surface and groundwater quality is deteriorating day-by-day in Pakistan. The indiscriminate discharge of industrial and domestic wastewater into open water bodies and groundwater is the main threat to the country's water reserves. The absence and non implementation of legislative measures and standards has been the root cause of the deterioration in water quality observed over the years. The issue is becoming very serious, as many aquifers and open water bodies, like lakes, rivers and streams, are being increasingly contaminated by pollutants from industrial, agricultural and municipal wastes.

At present, groundwater resources are being contaminated in many ways. Contamination of fresh water due to lateral and horizontal movement of saline water, drainage effluents and disposal of saline water into canals are also becoming a great threat. Industrial and municipal effluents are recognized as major sources [2]. Disposal of industrial waste is continuously adding heavy metals and trace elements into groundwater aquifers, and surface water bodies are also indirect sources of contamination for groundwater. Municipal solid waste sites in all the cities are the permanent source of organic and biological pollution. The threat from waterborne diseases is highlighted in the '*Mansoon*', when the spread of *E. Coli* bacteria in drinking water results in several deaths and a large number of ill people [3].

Contamination of pathogens in drinking water is one of the most souring issues in Pakistan. Both the surface and groundwater contain microorganisms which cause diseases such as typhoid, cholera, dysentery and diarrhea [4]. Many epidemics have been attributed to waterborne diseases, especially in developing countries. Water borne diseases are the largest killers in the country and health problems resulting from polluted water cost a large amount of money. One of the main causes of waterborne diseases in Pakistan is due to lack of proper sanitation system [1]. Inadequate facilities for excreta disposal reduce the potential benefits of safe water supplies [5]. The unhygienic disposal of human excreta may lead to the contamination of the groundwater source. Onsite sanitation systems are the major cause of microbial contamination of groundwater in Pakistan [6]. Onsite sanitation (drop and store) provides the most obvious pathway. These systems effectively concentrate and store large volumes of fecal material in one place, often in an unlined storage chamber, providing a potential point source of contamination. Where hydraulic loading is sufficient (i.e. where urine, wash water or rain water is mixed with the solid waste), pathogens may potentially move down to the water table. This is particularly likely where the depth to groundwater is shallow, and is inevitable if the base of the storage chamber intersects the water table.

Problem Statement

Almost all the public water supply systems in Lahore use groundwater as a primary source. A full assurance that drinking water is not fecally contaminated is a core issue for any drinking water system. Viral contaminants, because of their small size and persistence in the environment, may be more of a threat to groundwater than bacterial or protozoan contaminants associated with fecal contamination.

The city of Lahore with a population of about 5046 million produces about 1473 x 10^3 liters/day of sewage [7]. A sizable portion of it is disposed of through septic tanks and soakage pits in the ground. A survey indicates a marked rising trend in water borne diseases; this trend may be due to an extensive use of soakage pits along with extraction of water from shallow groundwater aquifers. This risk doubles when there is a practice of connecting the soakage pit with the groundwater table. Using galvanized iron pipes for water distribution is also contributing its share in contaminating drinking water. These service pipes run along the open drains and serve the dwellings in Lahore. Galvanized Iron (G.I) pipes tend to deteriorate more rapidly in moist conditions than other types of pipes used for same purpose, also allowing the drain water to seep into the pipe [7]. Other sources of fecal contamination of groundwater supplies originate from a variety of sources including onsite septic systems; domestic sewer line breaks, overland flow from urban, agricultural and natural areas, '*leachate*' (obnoxious liquid produced from solid waste dumping or sanitary landfills) and recharge from surface waters or reclaimed wastewater [1].

Objective

The research was conducted to aid in the development of microbial groundwater quality and to fill the gap of information on the occurrence and factors related to the presence of '*feacal*' contamination and their indicators in aquifers serving public water supplies. Numbers of cases of waterborne diseases are compared between areas having proper sewerage system and the areas in which soakage pits and shallow hand pumps are used. This data is co-related with the test results of sampled water to prove that poor sanitation practices are the major cause of waterborne diseases.

Testing Facilities

The following mentioned tests were conducted in the laboratory of "Institute of Environmental Engineering and Research" (IEER), UET Lahore to visualize the field situation.

a) Total Coliform test

b) E-coli test

Methodology

The objective of this study was to find a relationship between poor sanitation practices and waterborne diseases in the area. For this purpose, Lahore City was divided into four zones on the basis of living standards of people and availability of medical facilities. Posh areas of Lahore city are provided with proper sanitation facilities, while others contain outdated sanitation systems. Comparison of groundwater quality in terms of *"feacal"* contamination and number of cases of waterborne diseases in both kinds of areas hopefully prove the objective of the study.

The first phase of the study was the collection of data from a general survey. This was about congregation information about the trends in waterborne diseases from doctors, health workers, officers of health department, etc. Information about the localities comprising soakage pits and faulty sewerage systems from WASA (Water and Sanitation Agency) were also collected. For collection of sample from distribution system, water supply lines were flushed sufficiently to ensure that the sample was representative of the supply. For collection of samples from tube wells, precautionary measures were adopted to ensure the representative sample of tube well.

Introduction to Study Area

The population increment of Lahore city leads to the trigger of new problems. One of them is out breaks of waterborne diseases. It is universally believed that a sanitation system plays a vital role in the health of a community [2]. WASA is responsible to provide sanitation services for the people of Lahore. The areas which are selected to examine were *Walled City, Garden Town, Faisal Town, Model Town, Township, Multan Chongi, Muzang, Ichra, Ghorey shah, UET, Begum Pura* and *the Gulberg* area etc. These areas were selected on the basis of differences in life style, degree and conditions of sanitation and health facilities provided. As mentioned, the city was divided in to four zones according to the availability of medical facilities. These zones are co-related by the name of the major hospital situated in that area.

Zone-I (Jinnah Hospital)

This hospital serves the areas of *Garden Town, Faisal Town, Model Town, The University of Punjab Campus*, and *Township* etc. From here diagnosis like vomiting, diarrhea, loose motion, gastrointestinal problems, etc., gave the count of number of cases of waterborne diseases through the year as explained in Table-1 and Fig-1 below:

Table 1: Treatment of percentage waterborne disease cases at Jinnah Hospital

Months	% Waterborne Diseases	Months	% Waterborne Diseases	Months	% Waterborne Diseases
January	17.86	May	25.8	September	23.45
February	18.18	June	22.99	October	16.47
March	13.77	July	24.65	November	14.45
April	18.94	August	22.98	December	13.19

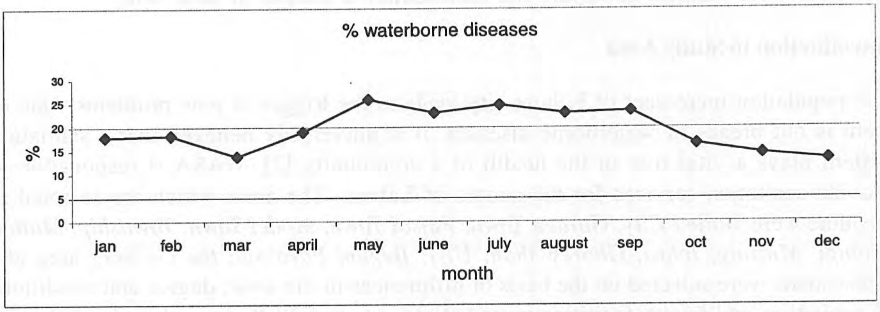

Fig. (1): Plot of % Waterborne Diseases Vs Months (For Zone-I)

Laboratory results of different water samples taken from Zone-I are presented here below in Table-2.

Table 2: Coliform and E-Coli Test Results (MTFT)

(Zone-I) *Garden Town Area*	Source		Dilutions			Results
(No of samples 4)						MPN/100
			10 ml	1 ml	0.1 ml	ml
Sample No. 1	(Tube well)	T.C	0	0	1	2
(Tube well No. 279)		C.C	0	0	0	0
(Approximate depth up to 750 feet).		E.C	0	0	1	2
Sample No. 2	(Tube Well)	T.C	0	0	0	0
(Tube well No. 279)		C.C	0	0	0	0
(Approximate depth up to 750 feet).		E.C	0	0	0	0
Sample No. 3	(Dist. System)	T.C	0	1	1	0
Distribution system, house no 63/9		C.C	0	0	0	0
Campus Road, Punjab University		E.C	0	0	0	0
Sample No. 4	(Dist. System)	T.C	0	0	0	0
Distribution system, house No. 63/9		C.C	0	0	0	0
Campus Road, Punjab University		E.C	0	0	0	0

(As per WHO Guidelines for drinking water total coliforms and e-coli /100 ml in an occasional sample should be zero).

Results show that ground water is contaminated but distribution system is safe for drinking water due to chlorination. We can not rely on distribution system because the scenario is totally different for posh areas and underdeveloped areas in the same zone.

Zone-II (Services Hospital)

Data collected from the Services Hospital, which is representing the Zone-II is explained in Table-3 and Fig-2. This hospital serves the major areas like *Gulberg, Muzang, Ichra, Shadman and Jail Road etc.*

The results of collected samples from Zone-II are presented in Table-4 below, which show that the distribution system is contaminated due to different reasons.

Table 3: Treatment of percentage waterborne disease cases at Services Hospital

Months	**% Waterborne Diseases**	**Months**	**% Waterborne Diseases**	**Months**	**% Waterborne Diseases**
January	19.67	May	28.30	September	21.97
February	19.70	June	27.03	October	16.22
March	15.76	July	28.11	November	14.37
April	22.43	August	24.93	December	13.71

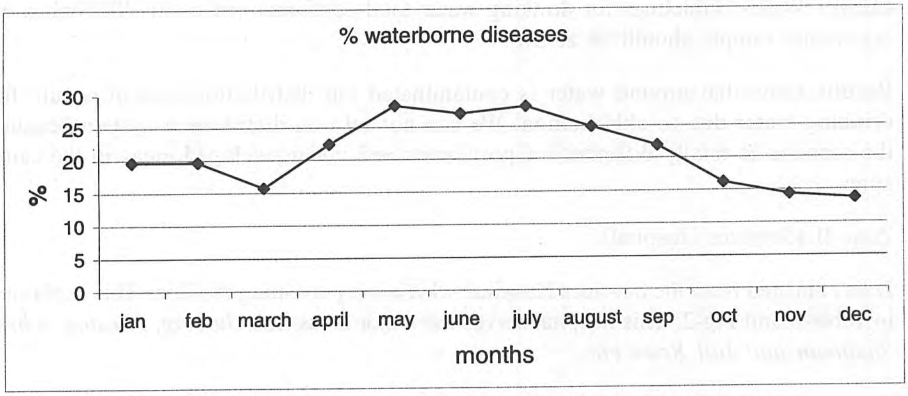

Fig. (2) Plot of % Waterborne Diseases Vs Months (For Zone-II)

Table 4: Coliform and E-Coli Test Results (MTFT)

(Zone-II) *Muzang Area*	**Source**		**Dilutions**			**Results**
(No of samples 3)						MPN/100
			10 ml	1 ml	0.1 ml	ml
Sample No. 1	(Tube well)	T.C	0	0	0	0
Tube Well, *Chaudary Colony*		C.C	0	0	0	0
Kachi Abadi.		E.C	0	0	0	0
Sample No. 2	(Dist. System)	T.C	1	0	0	2
Darbar Takiya Baba Behram Shah		C.C	1	0	0	2
		E.C	1	0	0	2
Sample No. 3	(Dist. System)	T.C	0	0	0	0
12-B *Jail Road* Lahore		C.C	0	0	0	0
		E.C	0	0	0	0

Sample No. 2 (Zone-II) shows coliform count; this might be due to the presence of overhead tanks. These tanks are built to provide water in case of water shortage or during the time of peak water use.

Zone-III (Nawaz Sharif Hospital)

All old residential areas of Lahore City are included in this zone. Total numbers of cases of each disease were kept on an annual basis in Nawaz Shraif Hospital. Main areas included in Zone-III are *Walled City, Circular Road,* and *Badami Bagh* etc. Data collected from this zone is presented in Table-5. The results of collected samples are explained in Table-6 below, which shows the contamination of the distribution system and groundwater at shallow depth.

Zone-IV (Ganga Ram Hospital and Shalimar Hospital)

The main areas included in this zone are *Mall Road, Anarkali, Ghorey shah, Station, Begum Purra Mughal Purra,* etc. The registered cases of HEV (Hepatitis E Virus) and HAV (Hepatitis A Virus) at Shalimar Hospital are listed below in Table 7.

Table 5: Number of Patients of Waterborne Diseases at N.S Hospital

Diseases	No of patients	% Of Waterborne cases
Dysentery	83	0.53
Vomiting	398	2.5
Abdominal Pain	105	0.67
Gastrointestinal	61	0.39
Diarrhea	5295	34.03
Total	**15559**	**38.12**

Table 6: Coliform and E-Coli Test Results (MTFT)

Walled City (Zone-III)	Source		Dilutions			Results
(No of samples 3)						MPN/100
			10 ml	1 ml	0.1 ml	ml
Sample No. 1	(Boaster Pump)	T.C	4	0	0	13
Boaster pump , *Masjid Bagh Wali*		C.C	4	0	0	13
		E.C	4	0	0	13
Sample No. 2	(Dist. System)	T.C	1	0	0	2
Distribution system		C.C	1	0	0	2
A tap, *Circular Road Mochigate*		E.C	1	0	0	2
Sample No. 3	(Tube well)	T.C	0	0	0	0
New Shah Alam Gate, Tube well		C.C	0	0	0	0
		E.C	0	0	0	0

Table 7: Number of Hepatitis Cases Served In Shalimar Hospital During Year 2002

Type of case	Number of suspected cases	Number of conformed cases
Anti HEV	31	21
Anti HAV	41	8

The laboratory results of collected water samples from Zone-IV are noted in the Table-8, which show a high contamination of the distribution system, as well as the shallow groundwater source. Sample No.1 was taken from a hand pump with an approximate depth of 250 feet. It showed a high coliform count, confirming groundwater contamination. Sample No. 2 from a tube well also showed presence of coliforms, the depth of tube well is approximately 750 feet. Serious contamination of groundwater is taking place in this area, and might be due to the extensive use of soakage pits and leaking sewers and blocked manholes. The distribution system showed a very high coliform count. Such a high contamination in the distribution system can be due to infiltration of sewage into water mains.

Present situation in study area

In Lahore particularly there are two basic methods (on site disposal and off site sanitation) of excreta disposal, which are popular or favorable according to local conditions [7]. In areas of *Defense* and *Cantonment*, which have yet not been fully developed, it is instructed by the authorities to construct septic tanks as an integral part of house at the expense of plot owner. Septic tanks are known to reduce the problems of a sewerage system up to 80 percent by accomplishing primarily digestion of the waste [1]. In the areas which fall in the category of slums, soakage pits are more common due to the poor sewerage system. Faulty septic tanks and soakage pits pose the same hazards to environment, their remedial measures are also same.

Table 8: Coliform and E-Coli Test Results (MTFT)

***Ghorey Shah* (Zone-IV)**	**Source**		**Dilutions**			**Results**
(No of samples 3)						MPN/100
			10 ml	1 ml	0.1 ml	ml
Sample No. 1	(Hand pump)	T.C	5	4	0	130
Hand pump		C.C	5	4	0	130
57-B Ghorey Shah Road,		E.C	5	4	0	130
Sample No. 2	(Tube well)	T.C	0	0	1	2
Tube well No 87,		C.C	0	0	1	2
Ghorey Shah Chowk		E.C	0	0	1	2
Sample No. 3	(Dist.system)	T.C	5	4	4	350
Distribution System		C.C	5	4	4	350
Ghorey Shah Darbar		E.C	5	4	2	220

Conclusions and Recommendations

Some major conclusions are derived from this research. Human health is very much impacted by unsafe drinking water and poor environmental sanitation. Diseases related to polluted drinking water, unhygienic food preparation, improper excreta disposal and unclean household environments constitute a major burden on the health of peoples in Lahore. The main conclusions and recommendations are mentioned below:

- Development in water supply and sanitation systems without proper maintenance and rehabilitation is not meeting the needs of the people.
- Leakage of water mains is one of the major causes of pollution in the water distribution system in Lahore.
- The habitants that use their own overhead roof tanks should be educated about the regular cleaning and chlorination.
- Galvanized iron pipes should be replaced with proper material service pipes. Illegal water connections are also causing a poor quality water in distribution systems, hence should be controlled by the authorities.

- The natural drains, which have been clogged or out of service for many reasons, should be rehabilitated and lined properly so that they do not contaminate groundwater.
- Broken sewers are the major source of groundwater contamination at shallow depths in case of off site sanitation. Thus, a sewerage system should be maintained properly.
- It is very essential that the responsible agencies should provide proper service irrespective of the social status of the served area.
- Chlorination in one of the most effective and popular methods, practiced throughout the world. If only chlorination was practiced, it would eradicate a large percentage of water borne diseases.

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Groundwater management: modelling of salt transport with the TVD schemes

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GROUNDWATER MANAGEMENT: MODELLING OF SALT TRANSPORT WITH THE TVD SCHEMES

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ABSTRACT

A bidimensional model has been used in order to simulate the contaminant transport in the coastal groundwater area (Atlantic margin, Rharb Basin of Morocco). This groundwater is materialized by the salt contamination derived by several factors: evapotranspiration, lithological formation, marine intrusion, and interaction processes (water-rocks). In order to reduce the numerical diffusion and limit numerical dispersion, the slope limiter Superbee (TVD scheme) was implemented and applied to this zone. Results show that the Superbee slope limiter is efficient to draw the path of the contaminant front with high accuracy.

This method allows one to evaluate the concentration according to space and time. It constitutes an approach in water management and allows one to envisage risks of pollution and to manage the groundwater resource from the durable development perspective.

Keywords: Groundwater, Transport contaminants, Slope limiters, Simulations, Modelling, Managements, Morocco.

1. Introduction

Numerical modelling plays a paramount role in groundwater management (groundwater flow and the transfer of the pollutants). The resolution of the convective-diffusive equation by the traditional methods (Lax Wendroff and centred schemes) constitutes a problem on the level of numerical instability and numerical dispersion. It was shown that it is possible to reconstitute in a modelling field the concentration according to time **[1]**. Other methods which relate to the resolution of the elliptic equations of the temporal moments [2] were proposed within the framework of the forecast of the risks of the groundwater water pollution.

In order to understand the transport of the contaminant, the equation convection-diffusion was employed and applied in two cases: near and far from the coastal line. In this paper, one of the slope limiters schemes (Superbee) which was used firstly in gas dynamic modelling is presented. This method combines stability and precision corresponding respectively to schemes of first and second order. They reduce the numerical diffusion introduced by the space discretization and the numerical dispersion introduced through truncation errors due to the third order derivatives.

2. Transport equation

The transport equation of concentration (C) with a purely convection term in a flow with velocity $\vec{V}(u,v)$. is given by the following equation:

$$\frac{\partial C}{\partial t}+u\frac{\partial uC}{\partial x}+\frac{\partial vC}{\partial y}=0 \quad \text{V} \qquad \textbf{(1)}$$

Where u and are the velocity components in x- y-directions, respectively. The time stepping of the Equation (1) in spatially discretized from gives:

$$C_{i,j}^{n+1}=C_{i,j}^{n}+\alpha_{i-\frac{1}{2}j}^{n}(C_{i,j}^{n}-C_{i-1,j}^{n})+\beta_{i+\frac{1}{2}j}^{n}(C_{i+1,j}^{n}-C_{i,j}^{n})+\lambda_{i,j-\frac{1}{2}}^{n}(C_{i,j-1}^{n}-C_{i,j}^{n})+\mu_{i,j+\frac{1}{2}}^{n}(C_{i,j+1}^{n}-C_{i,j}^{n}) \qquad \textbf{(2)}$$

Where

$$\begin{cases}\alpha_{i-\frac{1}{2},j}^{n}=\alpha(C_{i-2,j}^{n},C_{i-1,j}^{n},C_{i,j}^{n},C_{i+1,j}^{n})\\ \beta_{i+\frac{1}{2},j}^{n}=\beta(C_{i-1,j}^{n},C_{i,j}^{n},C_{i+1,j}^{n},C_{i+2,j}^{n})\\ \lambda_{i,j-\frac{1}{2}}^{n}=\lambda(C_{i,j-2}^{n},C_{,j-1}^{n},C_{i,j}^{n},C_{i,j+1}^{n})\\ \mu_{i,j+\frac{1}{2}}^{n}=\mu(C_{i,j-1}^{n},C_{i,j}^{n},C_{i,j+1}^{n},C_{i,j+2}^{n})\end{cases} \qquad \textbf{(3)}$$

Scheme **(2)** is monotonic if:

$$\alpha_{i-\frac{1}{2}j}^{n}\geq 0\ ;\ \beta_{i+\frac{1}{2}j}^{n}\geq 0\ ;\ \lambda_{i,j-\frac{1}{2}}^{n}\geq 0\ ;\ \mu_{i,j+\frac{1}{2}}^{n}\geq 0 \qquad \textbf{(4)}$$

Spekreijse [3] has also shown that a 2D explicit monotonic scheme is not necessarily TVD. However, numerical experience [3] has shown that 2 D schemes using the splitting technique (1-D second-order accurate TVD scheme in each direction perpendicular to the cell's face) give oscillation-free accurate results.

For algorithmic simplicity, the 2D extension of flux-limiting schemes as splitting mode in each direction was used. The application of this technique to Equation (1) with the cell-centred finite volume discretization gives the semi-discrete equation:

For algorithmic simplicity, the 2D extension of flux-limiting schemes as splitting mode in each direction was used. The application of this technique to Equation (1) with the cell-centred finite volume discretization gives the semi-discrete equation:

$$\frac{dC_i}{dt}\Delta x\Delta y = -[uC]_{i-\frac{1}{2},j}^{i+\frac{1}{2},j} - [vC]_{i,j-\frac{1}{2}}^{i,j+\frac{1}{2}} \tag{5}$$

The interface values $C^n_{i\mu\frac{1}{2},j}$ and $C^n_{i,j\mu\frac{1}{2}}$ for arbitrary velocity fields are given as follows:

$$C^n_{i+\frac{1}{2},j} = \begin{cases} C^n_{i,j}+\frac{1}{2}\left(C^n_{i+1,j}-C^n_{i,j}\right)\psi\left(\theta^+_{i+\frac{1}{2},j}\right) & \text{if } u_{i+\frac{1}{2},j}\geq 0 \\ C^n_{i+1,j}-\frac{1}{2}\left(C^n_{i+1,j}+C^n_{i,j}\right)\psi\left(\theta^-_{i+\frac{1}{2},j}\right) & \text{if } u_{i+\frac{1}{2},j}<0 \end{cases} \tag{6}$$

$$C^n_{i,j+\frac{1}{2}} = \begin{cases} C^n_{i,j}+\frac{1}{2}\left(C^n_{i,j+1}+C^n_{i,j}\right)\psi\left(\theta^+_{i,j+\frac{1}{2}}\right) & \text{if } v_{i,j+\frac{1}{2}}\geq 0 \\ C^n_{i,j+1}-\frac{1}{2}\left(C^n_{i,j+1}+C^n_{i,j}\right)\psi\left(\theta^-_{i,j+\frac{1}{2}}\right) & \text{if } v_{i,j+\frac{1}{2}}<0 \end{cases} \tag{7}$$

With

$$\theta^+_{i+\frac{1}{2},j} = \frac{C^n_{i,j}-C^n_{i-1,j}}{C^n_{i+1,j}-C^n_{i,j}} \quad ; \quad \theta^-_{i+\frac{1}{2},j} = \frac{C^n_{i+2,j}-C^n_{i+1,j}}{C^n_{i+1,j}-C^n_{i,j}}$$

$$\theta^+_{i,j+\frac{1}{2}} = \frac{C^n_{i,j}-C^n_{i,j-1}}{C^n_{i,j+1}-C^n_{i,j}} \quad ; \quad \theta^-_{i,j+\frac{1}{2}} = \frac{C^n_{i,j+2}-C^n_{i,j+1}}{C^n_{i,j+1}-C^n_{i,j}}$$

Where ψ is the limiter function.

The expression for $C^n_{i\mu\frac{1}{2},j}$ and $C^n_{i,j\mu\frac{1}{2}}$ should be obtained simply by substituting respectively the index *i* by *i*-1 in formula **(6)** and the index *j* by j-1 in formula **(7)**.

If the limiter function ψ satisfies the following conditions:

$$0\leq\frac{\Psi(\theta)}{\theta}\leq 2 \text{ And } 0\leq\Psi(\theta)\leq 2 \tag{8}$$

Then the scheme, given by **(6)** and **(7)**, is monotonic.

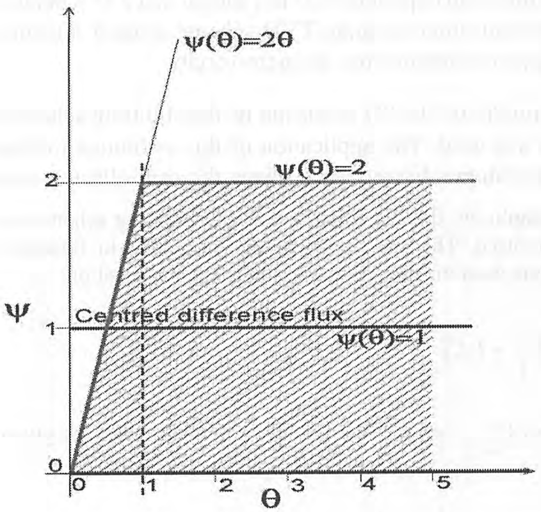

Fig. 1: Total Variation Diminishing region and the centred differences flux.

The region defined by (8) is shown in Figure 1 along with the limiter corresponding to the centred differences. Since this scheme is known to produce spurious wiggles in the solution with strong gradient variations, it is not surprising that this scheme is not uniform within the TVD region. Among the proposals, which have been discussed by Sweby [4] and Leveque [5], the limiter used in our study (Superbee) fulfill the constraints (8).

The Superbee limiter is obtained by the following limiter functions:

$$\Psi(\theta) = \mathrm{Max}(0; \min(1, 2\theta; \min(2, \theta))) \tag{9}$$

One can find details about other slope limiters for the convection equation in the book by Durran [6]. The Upwind scheme is used here in order to approximate the convective term and for comparing with the Superbee slope limiter.

3. Application of the Rharb region (Morocco)
The southern part of the Rharb basin is located between the Mediterranean Sea in the north (Fig. 2), the Hercynian Meseta in the south, and the Atlantic Ocean in the west. The temperature of the groundwater varied from 22.1 to 23.8 °C.

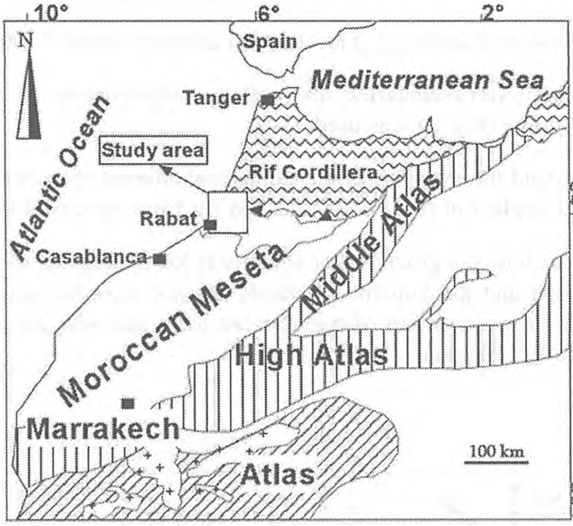

Fig. 2: Structural domains in Morocco.

The groundwater flows toward the north (Rharb basin) and toward the Atlantic Ocean. The hydrochemical analysis of the groundwater reveals several contaminants, in particular the contamination by chloride [9, 10]. Chloride contamination is caused by three principal sources: groundwater flow in the Pre-Rifean Nappes, marine intrusion and industrial activities.

For simplicity, comparison was made only with the upwind scheme to the Superbee limiter applied to the study area shown in Figure 2 and zoomed below Figure 3:

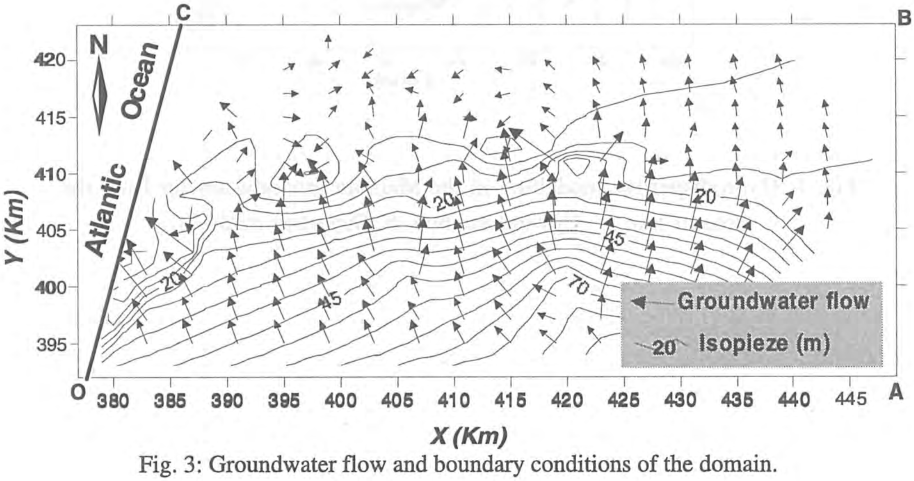

Fig. 3: Groundwater flow and boundary conditions of the domain.

In the studied area, the purely convection equation with the following initial and boundaries conditions was solved:

- At the initial time (t=0) and (x_0, y_0) location, an arbitrary value of 100 mg/l was used.
- At the (OA) and (AB) boundaries, the outflow condition and the no-permeability one at the (OC) line (Fig. 3) was used.

In order to understand the transport of the saline contaminant, the convection equation has been used and applied in two cases: near and far from the costal line (Fig. 4).

Far from the coastal line, the groundwater velocity is lower (Fig. 5), so the comparison between the Upwind and the Superbee methods has not recorded any difference. On the other hand, in the western part of the Mamora basin and near the coastal line, the groundwater velocity is higher.

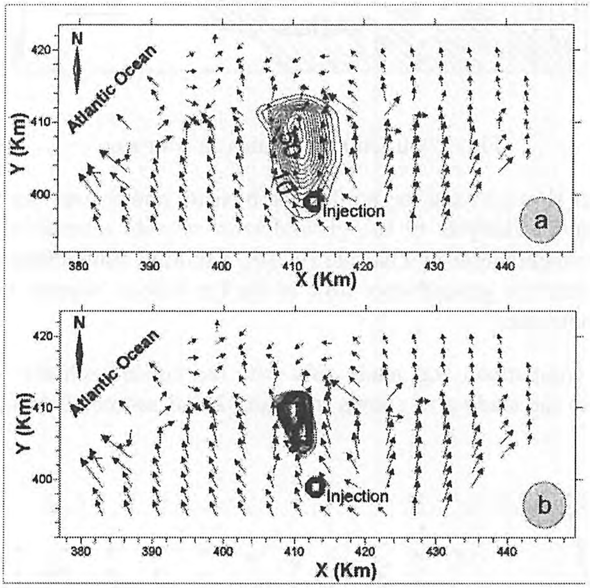

Fig. 4: Hydrodispertive modelling in the Mamora groundwater far from the coastal line (a. Upwind method, b. Superbee method).

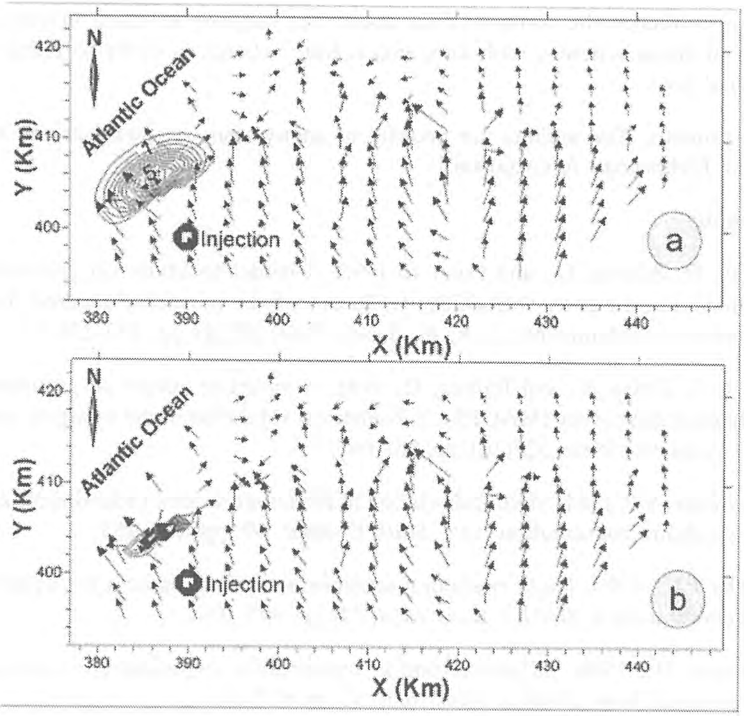

Fig. 5: Hydrodispertive modelling in the Mamora groundwater near the coastal line (a. Upwind method, b. Superbee method).

4. Results and Discussion

In this study, two simulations are presented: the first one examines the prediction of propagation of an accidentally pollution of the groundwater of the Rharb basin. For this case, we simulate two months propagation with an injection of 1 hour (surface infected is about 1 km^2). Figure 4.a shows that the upwind scheme exhibits an excessive and not realistic diffusion due to the numerical approximation of the convective term. For this scheme the infected surface is about 252 through the North and following the flow direction. In Figure 4.b and as well known, the Superbee limiter shows less diffusive propagation and the infected surface is only about 70. Consequently, the Supebee slope limiter is more conservative than the Upwind scheme. The second simulation concerning the saline intrusion from the Atlantic Ocean (Figure 5) shows that the intrusion of ocean salinity is less dramatic because the flow is in the direction of the Atlantic Ocean and saline water is retained in the vicinity of the coast.

5. Conclusion

In this study, the Upwind scheme (first order scheme) was compared with a higher-order TVD flux limiter scheme (Superbee). This limiter scheme has the ability to limit the numerical diffusion and reduces the numerical dispersion introduced by the third-derivative term due to truncation errors. The Superbee provides a best result concerning the propagation of the pollutant, but from the management risk point of view, it is better to use the Upwind approximation to predict the contamination surface. This scheme over-estimates the contamination zone. Our ongoing research involves the application of these schemes with an implicit time scheme in order to reduce the computational cost.

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Pore-Network Model Simulating the Concurrent Flow of Three Immiscible Fluids

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PORE-NETWORK MODEL SIMULATING THE CONCURRENT FLOWOF THREE IMMISCIBLE FLUIDS

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ABSTRACT

Predictive field-scale models of the concurrent flow of three fluids require accurate predictions of five macroscopic flow descriptors: three relative permeabilities and two capillary-pressures as functions of the fluid saturations and saturation history. Since direct measurement of these descriptors is very difficult, and empirical correlations are often unreliable, the use of physically-based pore-scale models has become an appealing alternative. In this paper, we describe the features of our quasi-static pore network model for three immiscible fluids. The model integrates a realistic representation of pore connectivity and morphology reconstructed from 3D micro-focused X-ray CT images, a realistic description off fluid displacement mechanisms, and a sound representation of the wetting properties of the rock. All pore-level displacement mechanisms: piston-type, Snap-off, cooperative pore-body filling, and double-displacements are considered with arbitrary contact angles and spreading coefficients. The proposed model is used to simulate gas injection into water-wet permeable rocks that initially contain water and NAPL after two-phase drainage followed by two-phase imbibition. The gas injection is performed using a cluster-based invasion percolation algorithm with trapping. The strong influence of the two-phase saturation history on the three-phase transport properties of a permeable rock is illustrated by performing a series of gas injections into Bentheimer sandstones with different initial NAPL and water saturations, and different microscopic fluid interface configurations.

Keywords: NAPL, 3-phase flow, pore network models, imbibition, sandstone

1 Introduction

Three-phase flow in porous media is important in many cases: gas injection and thermal flooding in oil reservoirs (petroleum engineering), flow of non-aqueous phase liquids (NAPL) in the vadose zone (environmental engineering), vapor extraction in soil (environmental engineering), Radio-nuclide migration from hot repositories of nuclear waste (chemical engineering), etc... Predictive field-scale models of the concurrent flow of three fluids require accurate predictions of the macroscopic relative permeabilities, capillary pressures, and special distributions of trapped fluids. Experiments with three-phase flow are difficult, expensive, and time consuming. Furthermore, it is impractical to measure relative permeabilities for *all* possible saturation paths that may occur in a three-fluid flow system. Instead, empirical correlations of three-phase relative permeabilities and capillary pressures have been obtained from the interpolations of two-phase, NAPL-water and NAPL-gas, flow experiments [5, 21, and 27]. The empirical nature and incomplete physics of these three-phase models [13] render them insufficient to predict the general three-phase flow behavior.

A physically-based three-phase pore network model is an appealing alternative to the empirical correlations of measured relative permeabilities and capillary pressures [8, 9, and 26]. Common to all these three-phase pore network models is that they have been performed on regular 2D or 3D lattices. Only Lerdahl et al. [15] used a reconstruction algorithm based on thin-section analysis to generate a topologically disordered network. Their pore network model illustrated a very promising comparison between the model and experimental three-phase relative permeabilities on Berea sandstone during gas injection after two-phase primary drainage [17, 18]. However, their model has not included gas injection after two-phase secondary imbibition in which NAPL exists as many trapped clusters. Recently, Piri and Blunt [25] have also developed a three-phase flow model on the same network constructed by Lerdahl et al. [15]. Piri & Blunt's pore network model has ignored double and multiple displacements; they only considered gas injection for relatively high NAPL saturations, and with little or no NAPL initially trapped. Here, we attempt to reproduce the Lerdahl et al. [15] model and extend it to simulate gas injection after secondary imbibition.

2 The Network and Two-Phase Flow Model

The pore network we use [2, 3, 22, 24] is a realistic representation of a sample of Bentheimer sand-stone reconstructed from the 3D micro-focused X-ray CT image. The network is a courtesy of Statoil Company. It consists of cylindrical *ducts* with angular cross-sections. The complex topology and geometry of the network is detailed in [19, 22]. The two-phase flow model is quasi-static,i.e., capillary forces dominate, gravity is accounted for, and the effects of viscous forces are ignored. The flow simulations proceed in the following sequence: (1) fully saturate the network with water, (2) perform primary drainage (i.e., oil displaces water) up to a predefined maximum capillary pressure, (3) alter wettability, and (4) perform secondary imbibition (i.e., water displaces oil).Capillary pressure curves are calculated using percolation algorithms [3] with piston-type, snap-off, and cooperative pore-body filling mechanisms [19, 22]. Relative permeabilities are calculated using Darcy's law and accurate expressions of the hydraulic conductance of phases bulk flow [24], corner flow [23], and intermediate layers flow [1]. Spatial distribution of oil clusters are identified using the Hoshen-Kopelman algorithm [10] extended by us to disordered networks [2].

3 Assumptions for the Three-Phase Flow Model

More detailed description of the physics of three-phase flow is yet to be uncovered. However, great deal of it has been recently recognized from micromodels and other experiments. Here, we present and discuss the physics and main assumptions implemented in our three-phase flow model. The discussion includes the spreading coefficient, three-phase contact angles, displacement mechanisms, capillary entry pressures, and saturations paths.

3.1 Spreading Coefficient and Admissible Three-Phase Contact Angles

An important characteristic of three-phase flow is the existence of layers of the intermediate fluid sandwiched between the two other fluids. For example, in Figure 2G, the intermediate layers of oil are sandwiched between the water that resides in the corners of the pore and gas which occupies the center of the pore [7, 30]. The existence or absence of such NAPL layers is related to the equilibrium spreading coefficient, contact angles, capillary pressures, and pore geometry [1, 6, 16, 29]. The question that immediately arises is what possible values of contact angles one should assign? There is yet *no* direct answer to this question. For specific systems, there have been attempts to relate contact angles to the interfacial tensions and spreading coefficient [4, 12, and 15]. In our simulator, similar to Lerdahl et al. [15], q ow, q go, and q gw are all defined *randomly* from a uniform probability distribution function, scaled to different ranges. We believe that this is the best we can do at this stage until the *quantitatively* new theories of three fluid phase-solid wetting behaviors appear.

3.2 Initial Conditions

We restrict this study to the initial condition that corresponds to a network of water and NAPL with a specific initial water saturation, Swi, and specific initial o/w configuration. The network initial o/w configurations are set by the NAPL-water drainage or imbibition processes and the last o/w capillary pressure attained during each of these two processes. After primary drainage of an initially water-wet rock, NAPL exists as one cluster that may or may not span the network depending on the maximum capillary pressure attained during the NAPL invasion. In contrast, after secondary imbibition, NAPL exists as many disconnected clusters. Our results indicate that the number and spacial distribution of the trapped NAPL clusters has a considerable impact on the three-phase flow characteristics.

3.3 Fluid Con_gurations

At the end of three-phase primary drainage or secondary imbibition, and depending on o/w contact angle, the water and oil configuration in a duct is one of the four possible configurations depicted in Figure 1. Configuration A is a duct completely filled with water, B is a duct with water in the corners and oil in the center after primary drainage or spontaneous imbibition, C is the same as B but after forced imbibition, and D is a duct with water in the corners and the center and oil in the intermediate layers after forced imbibition with extreme o/w contact angles. When gas is introduced into the system, the displacement is always piston-type advance because gas is not initially present in the system and it is non-wetting. Therefore, gas will only occupy the center of the pore.

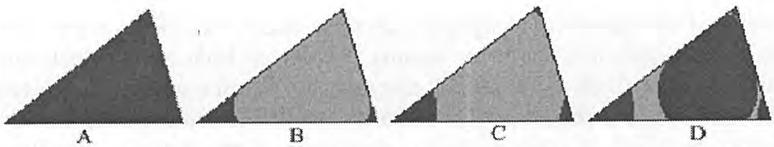


Figure 1: Possible *o/w* configurations in a duct after the secondary imbibition ends (water is dark and NAPL is gray)

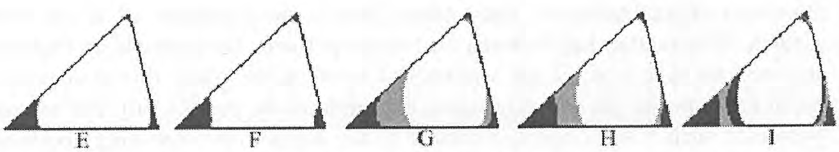


Figure 2: Possible g/o/w configurations in a duct during gas invasion (water is dark, NAPL is gray, and gas is white)

Hui and Blunt [11, 12] showed that gas invasion into the o/w configurations shown in Figure 1 results into five additional g/o/w configurations, Figure 2. Details of these fluid configurations and their threshold capillary entry pressures are described and defined in [11, 15]. In this analysis, we assume that a fluid-water interface is pinned along the boundary of the region of altered wetta bility. This interface adjusts its curvature until it reaches the new prescribed contact angle. We now assume that the new receding cqontact angle is larger and, therefore, water can be displaced completely from the corner if $q + bi\ {}^{3}\ p\ /2$. The phase saturations and conductance are calculated using the procedures described in [3] and [1].

3.4 Fluid Clusters and Their Displacement Mechanisms

At the end of the two-phase flow (primary drainage or secondary imbibition), NAPL exists in four types of clusters: (I) clusters spanning the network, (II) clusters connected to the inlet but disconnected from the outlet, (III) clusters connected to the outlet but disconnected from the inlet, and (IV) clusters disconnected from the inlet and outlet. The NAPL clusters that are connected to the outlet face (I and III) are directly displaced by gas and collected at the outlet. This process is called *direct NAPL* displacement. In contrast, the NAPL clusters that are not connected to the outlet (I and IV) can only be displaced by multiple displacement mechanisms. In case of the fi*rst* gas injection into the system, micromodel experiments [14, 20, 28] have shown that the necessary multiple displacement is *double drainage* in which gas displaces NAPL and NAPL displaces water. Van Dijke et al. [28] have observed higher-order multiple displacements in the case of alternate cycles of gas and water injection. In general, one must consider all possible multiple displacements using a minimum path algorithm, and find the displacement sequence those results in the minimum capillary pressure. However, such a procedure is very demanding computationally when considering large, disordered networks. Our study is restricted to the first gas injection into the network, therefore it is sufficient to consider only the double drainage displacement mechanism. Incorporation of the double drainage displacement is quite difficult for two reasons: (1) tracking the boundaries of the moving trapped clusters, and (2) conserving the NAPL volume. These two problems are especially challenging in the network considered in this analysis because of its complex geometry and connectivity.

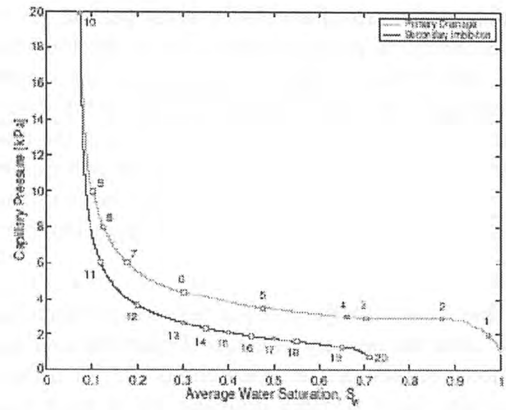


Figure 3: Gas injection after *o/w* primary drainage or secondary imbibition with different initial saturations (denoted by the squares)

4 Case Study

Here we present the results of different gas injection simulations after o/w primary drainage and secondary imbibition. All simulations have been performed with equilibrium interfacial tensions equal to 35´10-3 N/m for water, 25´10-3 N/m for oil, and 50´10-3 N/m for gas. These values indicate that the rock spreading coefficient is _10 mN/m. The water, oil, and gas densities are 1000, 950, and 1.2 kg/m^3, respectively. The o/w primary receding contact angles during primary drainage, q_{ow}, are 0° to 10°. The o/ w advancing contact angles during secondary imbibition, q_{ow}, are 10° to 30°. The o/w secondary receding contact angles during gas injection are q_{ow} 10° to 30°. The g/o receding contact angles q_{go}, and g/w receding contact angles, $q_{gw,}$ during gas injection are 0° to 10°. Notice that the values of these contact angles determine that the rock is water-wet. The maximum capillary pressure in primary drainage, $P_{c,ow}^{\max}$, and gas injection, , is 188000 Pa. For the relative permeability calculations, we assume 1.0 ´ 10-3 Pa-s for the water and oil viscosities, and 1.0´10-4 Pa-s for the gas viscosity. The o/w interface boundary condition is assumed no slip, whereas the g/o and g/w interface boundary condition is perfect-slip. The two-phase (water and oil) primary drainage and secondary imbibition capillary pressure curves are plotted in Figure 3. Gas injection simulations are performed with 20 different initial o/w saturations and interface configurations along these two curves. There are 10 simulations along the primary drainage curve, and 10 along the secondary imbibition curve. As mentioned earlier, after primary drainage, NAPL exists as a single cluster. After secondary imbibition, NAPL exists in many clusters.

5 Results of Gas Injection Simulations

Figure 4 compares the saturation paths obtained from both saturation histories. It is observed that the saturation paths obtained after primary drainage (Figure 4a) are more scattered, and those after secondary imbibition (Figure 4a) are less. Moreover, for gas injection after secondary imbibition the different saturation paths converge. In both cases, the trapped NAPL saturation reaches very small values, close to 1%, due to our assumption that one intermediate NAPL layer per duct is enough to maintain the local NAPL connectivity. In reality, connectivity of the intermediate NAPL layers is more complicated and tenuous. Figure 5 summarizes the invasion events in both sets of simulations (Figure 5a for primary drainage and Figure 5b for secondary imbibition) as functions of the initial water saturation, S_{wi}, at the onset of gas injection. As S_{wi} increases, *direct NAPL* decreases, *direct water* increases, and *double drainage* increases. As discussed before, the *double drainage* mechanism affects more gas injection after secondary imbibition because of the large number of trapped NAPL clusters.

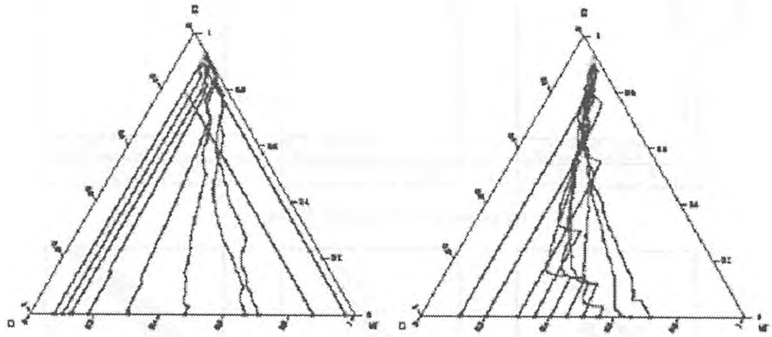
Figure 6 compares the water, NAPL, and gas relative permeabilities plotted against their own saturations after the primary drainage (Figure 6a) and secondary imbibition (Figure 6b) simulations. Although our calculations are for different sandstone, the relative permeability plots after primary drainage are in good qualitative agreement with the Statoil simulations of gas injection into Berea sandstone [15]. In the case of gas injection after secondary imbibition, one can immediately observe that the scatter of the relative permeabilities of NAPL is significantly larger than those of gas and water. This result demonstrates that the NAPL permeability in three-phase flow strongly depends on the saturation history. The water relative permeability is the least scattered indicating that it does not depend on the saturation history, i.e., it is only a function of its own saturation. The gas relative permeability has noticeable scatter especially at low gas saturations. Furthermore, it is observed that the NAPL permeability scatter after secondary imbibition is more severe than after primary drainage. We attribute this increased scatter to the internal movements and joining of the trapped NAPL clusters.

6 Discussions of Results

We begin with gas injection after primary drainage of water by NAPL.With high water saturations at the onset of gas injection ($S_w i = 0.97$ and 0.87), the invading NAPL cluster does not reach the outlet, and the major displacement process is *direct water*. There are no *direct NAPL* displacements. Some *double drainage* displacements are observed, but they do not succeed in moving NAPL all the way to the outlet face. Thus, NAPL saturation remains unchanged and its relative permeability is zero since the NAPL has not formed a spanning cluster. Assigning zero to the relative permeability of NAPL is somewhat misleading, since the NAPL is actually moving inside the network. The incorporation of the transient NAPL clusters into the oil relative permeability is impossible within the quasi-static framework of this analysis.

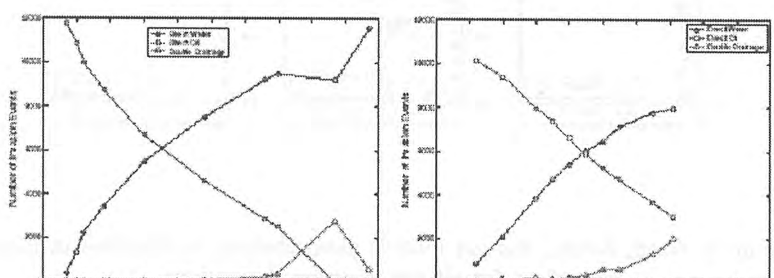
As the maximum capillary pressure in primary drainage increases, the relative permeability to gas also increases, and the water relative permeability decreases. Water relative permeability becomes very small as the water begins to flow predominantly in the continuous filaments along the duct corners. At lower water saturations, $S_w i = 0{:}70$

to 0.48, NAPL breakthrough occurs in two-phase primary drainage. Thus a network-spanning NAPL cluster is formed. Smaller NAPL clusters connected to the inlet face, but not to the outlet, may also be formed. In such cases, *direct NAPL* displacement is more favored than *double drainage* displacements. Therefore, it is observed that the number of *direct NAPL* displacements gradually increases and the number of *double drainage* displacements decreases. In general, the importance of *direct water* displacement decreases; however, *direct water* remains the major displacement mechanism because of the relatively high water saturation at the onset of gas injection.



(a) gas injection after primary drainage (b) gas injection after secondary imbibition

Figure 4: All saturation paths during gas injection with different initial water saturations and different two-phase displacement processes



(c) gas injection after primary drainage (d) gas injection after secondary imbibition

Figure 5: Direct water, direct NAPL, and double drainage events as function of initial water saturation from all gas injection simulations Relative Permeabilities, kr (a) gas injection after primary drainage

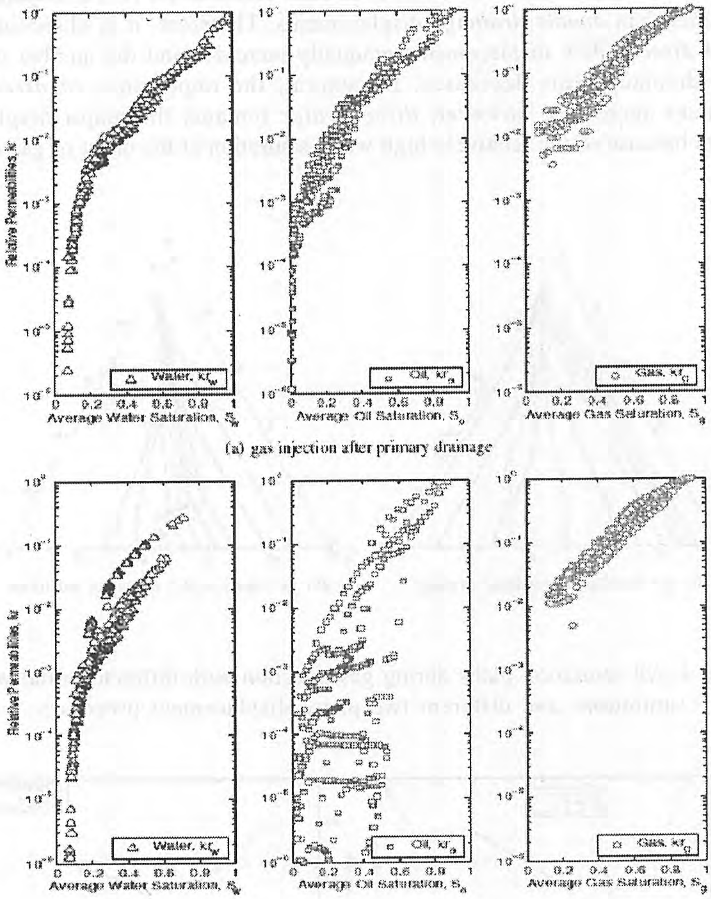


Figure 6: Water, NAPL, and gas relative permeabilities as functions of their saturations for all gas injection simulations

NAPL relative permeability decreases in a manner similar to that of water because the NAPL is allowed to flow in the intermediate layers, or NAPL filaments, in contact with the corner water filaments. However, it is observed that the NAPL relative permeability curves are not as smooth as those of water, because of the possible reconnection of NAPL clusters. For water saturations less than 0.30, NAPL exists in a large cluster connecting the inlet and outlet faces of the network. Therefore, *double drainage* displacements almost cease and the number of *direct NAPL* displacements exceeds that of *direct water* displacements. The gas and NAPL relative permeabilities are now similar to those in two-phase flow. The water relative permeabilities are very small because water flows entirely in the corner filaments.

During secondary imbibition displacement, the spanning NAPL cluster created during primary drainage is broken-up into smaller clusters by the bond-breaking mechanisms, such as snap-off and cooperative pore-body filling, e.g., [22]. It is expected that as secondary imbibition proceeds, more and more disconnected NAPL clusters are created. As a result, *double drainage* displacements enter the picture again and define the flow behavior. However, it is observed from our simulations that *direct NAPL* displacements are more favored than *double drainage*. Thus, initially the flow follows a saturation path with constant water saturation. Once further *direct NAPL* displacements become difficult, the frequency of *double drainage* increases, and water saturation. Once further *direct* NAPL displacements become difficult, the frequency of *double drainage* increases, and water saturation goes down.

One can also observe, as the initial water saturation increases, the number of *direct water* displacements increases due to the large amount of water in the network. For example, when $S_{wi} = 0.65$ to 0.71 at the onset of gas injection, the water saturation decreases and the oil saturation remains almost constant. NAPL is produced when the moving trapped clusters reach the outlet face. We note that the o/w capillary pressure increases in steps whenever a trapped oil cluster is displaced. We also note that the water and NAPL relative permeabilities have wider variability than the cases of gas injection after primary drainage. Moreover, the NAPL relative permeabilities increase in large steps whenever a trapped NAPL cluster connects with a spanning cluster. We call this effect the "weeping" NAPL relative permeability. A similar weeping effect was observed experimentally in the _ow of NAPL emulsions in water. The relatively large magnitude of step increases of the NAPL permeability is attributed to the small size of the network.

These observations on the phase relative permeabilities highlight the importance of not only the values of the initial two-phase saturations, but also of the initial fluid configurations exemplified by the respective cluster distributions. This conclusion is further illustrated by the fluid iso-permeability contours, or "isoperms," in Figure 7. These isoperms are linearly interpolated to preserve their actual shapes and avoid smoothing. The water isoperms, in most cases, depend only on water saturation. However, there are some situations, especially after secondary imbibitions, where this assumption fails. The gas isoperms are clearly curved and convex up. Therefore, the gas permeability *cannot* be described by its own saturation only. Finally, the NAPL isoperms definitely depend on two saturations.

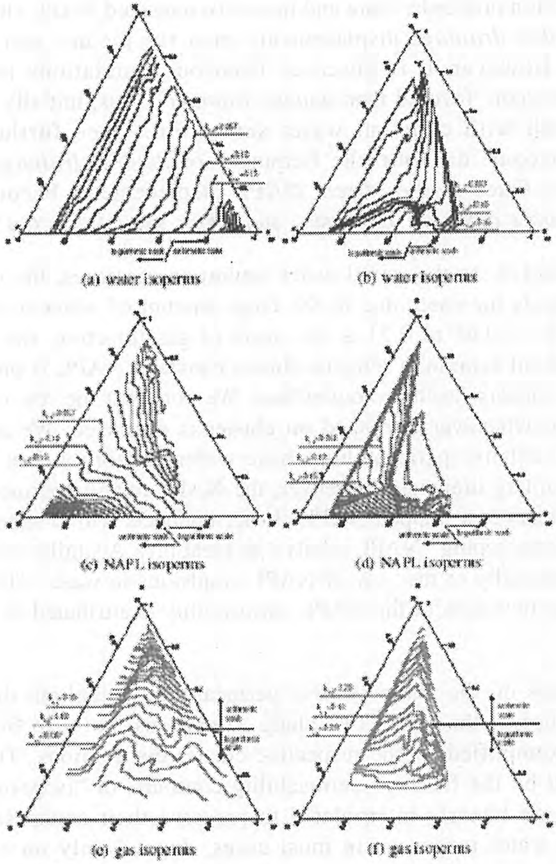


Figure 7: Water, NAPL and gas injection after primary drainage (left) and secondary imbibition (right).

7 Conclusions

- A complete quasi-static model of drainage of NAPL and water by gas in water-wet rocks has been developed. The model calculates the three fluid saturation paths, capillary pressures, and relative permeabilities. The model incorporates current state-of-the-art description of pore-scale displacement mechanisms and wettability.

- Our calculations clearly demonstrate that the saturation paths in three-phase drainage are very sensitive to the initial conditions, and depend on the prior saturation history. Therefore, pore network models should be used in the continuum three-phase flow simulators to generate the saturation-history-dependent relative permeabilities and capillary pressures.

- The trapped NAPL saturation after gas injection is very small, about 1%, consistent with our assumption that a single intermediate NAPL layer in a duct is enough to maintain the NAPL connectivity. This assumption is perhaps too optimistic and requires further study.
- The scatter of the three-phase saturation paths following primary drainage is wider than that after secondary imbibition. The different saturation paths converge, indicating that at high gas saturation the prior history is forgotten.
- The water isopermeability contours, or "isoperms", usually depend only on the water saturation. However, there are some instances of secondary imbibition, where these isoperms depend on two saturations. The gas isoperms are always curved. Therefore, gas permeability cannot be described by its own saturation only. Finally, the NAPL permeability de_nitely depends on two saturations, exhibiting a wide scatter when plotted against just the NAPL saturation.

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DEVELOPMENT & MANAGEMENT OF NATURAL WATER RESOURCES

b) SURFACE WATER RESOURCES

Hydrology of Wadi Systems

Howard S. Wheater

HYDROLOGY OF WADI SYSTEMS

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ABSTRACT

Throughout the arid and semi-arid areas of the world, wadi systems are under pressure. Water managers face the need to develop sustainable management options for limited resources. These resources face increased demand for water supply, increased risks from pollution and uncertainty over the future climate. Threats to ecosystems and water quality arise from over–abstraction and increased flood risks occur from floodplain development. Faced with these challenges, integrated management is needed. This requires a sound science base and appropriate decision support systems, including modelling tools. However, knowledge of the hydrology of wadi systems is limited and the available modelling tools have generally been developed for different climatic and hydrological conditions. This paper seeks to set out the state of knowledge of wadi hydrology, to identify the key gaps in knowledge and the research priorities, and to discuss the needs for, and the challenges of, the integrated modelling of wadi systems.

Keywords: wadi hydrology, integrated modelling, water resources management

INTRODUCTION

Although different names are used in different parts of the world, Wadi has come into global use to describe the ephemeral river systems that characterise the hydrological response of arid areas. Wadi is a word that stirs deep emotions. Wadi systems provide the life-giving water that has for millennia sustained human existence in a harsh environment. Wadis also provide landscapes with great beauty, and support not only human life but fragile and valuable ecosystems. However, throughout the arid and semi-arid regions of the world, wadi systems are under pressure. Water resources are limited, and demand for water is increasing, due to expanding populations, increasing per capita water use, irrigation and industrial development. Over-abstraction threatens the traditional (and sustainable) use of shallow and deep groundwater resources, and is in places associated with near irreversible degradation of water quality. Surface water and groundwater quality is threatened by point and diffuse pollution associated with increasing volumes of industrial and domestic waste and agricultural intensification. The ephemeral flows that characterise wadi response are infrequent, but can be extremely damaging, and the threat from floods to lives and infrastructure is increasing due to development within wadi floodplains. Urban development can more generally have dramatic and unforeseen consequences for wadi systems, for example due to the importation of water, leaks in water distribution and wastewater systems, and the discharge of treated and untreated effluents. Ecosystems are fragile, and under threat from groundwater abstractions and the management of surface flows. Added to these pressures is the uncertain threat of climate change.

In the face of these challenges, the integrated management of wadi systems is essential, considering both surface water and groundwater. This has been difficult to achieve, for technical and educational, as well as organisational and political reasons. Integrated management requires above all a sound science base, i.e. appropriate understanding of the surface and subsurface functioning of wadi systems, and secondly appropriate decision support systems, including modelling tools. This paper seeks to set out the state of knowledge of wadi hydrology, to identify the key gaps in knowledge and the research priorities, and to discuss the needs for, and the challenges of, the integrated modelling of wadi systems.

HYDROLOGICAL PROCESSES IN ARID AREAS

Data

Hydrology is a strongly data-dependent discipline, and despite the critical importance of water in arid areas, hydrological data have been severely limited. The lack of high quality observations is probably the main limitation in the development of arid zone hydrology (Pilgrim et al., 1988). There are good reasons for this. Populations are sparse and economic resources limited; the climate is harsh and hydrological events infrequent, but damaging. Ironically, the extreme variability of the climate is a principal reason why long records are essential. However, in the general absence of reliable long-term data and experimental research, there has been a tendency to rely on humid zone experience and data from other regions. This inevitably leads to inaccuracy and may result in inappropriate management solutions.

In recent years there has been significant progress in the development of national data networks, although problems of data quality remain a major challenge. There have also been some pioneering examples of experimental research. Together, these developments have given new insights into the unique features of wadi systems. The aim here is to review this progress and the resulting insights, and to consider the implications for integrated modelling of wadi systems.

Rainfall

Rainfall is the primary hydrological input, but rainfall in arid and semi-arid areas is commonly characterised by extremely high spatial and temporal variability. The temporal variability of point rainfall is well-known, at least for daily data. Although most records are of relatively short length, a few are available from the 19th century. Annual variability is marked and observed daily maxima can exceed annual rainfall totals. The availability of sub-daily data is more recent, but extensive analyses of Intensity-Duration-Frequency data have been carried out in the Gulf region. However, data are commonly archived as standard storm summaries of maximum intensities for a range of durations. Sub-daily time series data are increasingly important, but less generally available.

For spatial characteristics, information is much more limited. Until recently, the major source of detailed data has been from the South West USA, most notably the relatively small, densely instrumented basin of Walnut Gulch, Arizona ($150km^2$), established in the 1950s (Osborn et al., 1979) and still continuing. The dominant rainfall for this basin is convective; 70% of annual rainfall occurs from purely convective cells, or from convective cells developing along weak, fast-moving cold fronts, and falls in the period from July to September (Osborn and Reynolds, 1963). Raingauge densities at Walnut Gulch are currently better than 1 per $2km^2$. This has shown highly localised rainfall occurrence, with spatial correlations of storm rainfall of the order of 0.8 at 2km separation, but close to zero at 15-20km spacing.

Recent work has considered some of the implications of the Walnut Gulch data for hydrological modelling. Michaud and Sorooshian (1994) evaluated problems of spatial averaging for rainfall-runoff modelling in the context of flood prediction. Spatial averaging on a 4kmx4km pixel basis (consistent with typical US weather radar resolution) gave an underestimation of intensity and led to a reduction in simulated runoff of on average 50% of observed peak flows. A sparse network of raingauges (1 per $20km^2$), representing a typical density of flash flood warning system, gave errors in simulated peak runoff of 58%. The message is clear – without adequate representation of spatial rainfall data, modelling rainfall-runoff processes is severely compromised.

The extent to which this extreme spatial variability is a characteristic of other arid areas has been uncertain. Anecdotal evidence from the Gulf region underlay comments that spatial and temporal variability was extreme (FAO, 1981), but a pioneering study by the Ministry of Agriculture and Water, Riyadh, of five wadis in South West Saudi Arabia (Saudi Arabian Dames and Moore, 1988), confirmed this. The spatial rainfall distributions are described by Wheater et al. (1991a). The extreme spottiness of the daily rainfall is illustrated for Wadi Al-Lith in Figure 1. Typical inter-gauge spacings were 8-10km, and on half of the raindays only one or two raingauges experienced rainfall. For the more widespread events, sub-daily rainfall showed an even more spotty picture than the daily distribution (Figure 2). The frequency distribution of rainstorm durations shows a typical occurrence of one or two-hour duration point rainfalls, and these tend to occur in mid-late afternoon. Thus rainfall will occur at a few gauges and die out, to be succeeded by rainfall in other locations. In general, the storm patterns appear to be consistent with the results from the South West USA and area reduction factors were also generally consistent with results from that region (Wheater et al., 1989).

It is dangerous to generalise from samples of limited record length, but it is clear that most events observed by those networks are characterized by extremely spotty rainfall, so much so that in the Saudi Arabian basins there were examples of wadi flows generated from zero observed rainfall. However, there were also some indications of a small population of more wide-spread rainfalls, which would obviously be of considerable importance in terms of surface flows and recharge. This reinforces the need for long-term monitoring of experimental networks to characterise spatial variability.

For some other arid or semi-arid areas, rainfall patterns may be very different. For example, data from arid New South Wales, Australia have indicated spatially extensive, low intensity rainfalls (Cordery et al., 1983), and recent research in the Sahelian zone of Africa has also indicated a predominance of widespread rainfall (Lebel et al., 1997; Lebel and Le Barbe, 1997).

Rainfall-runoff processes

The lack of vegetation cover in arid and semi-arid areas removes protection of the soil from raindrop impact, and soil crusting has been shown to lead to a large reduction in infiltration capacity for bare soil conditions (Morin and Benyamini, 1977). In combination with the high intensity, short duration convective rainfall discussed above, extensive overland flow can be generated. This overland flow, concentrated by the topography, converges on the wadi channel network, with the result that a flood flow is generated. However, the runoff generation process due to convective rainfall is likely to be highly localised in space, reflecting the spottiness of the spatial rainfall fields, and to occur on only part of a catchment, as illustrated above.

Linkage between inter-annual variability of rainfall, vegetation growth and runoff production may occur. Our modelling in Botswana suggests that runoff production is lower in a year which follows a wet year, due to enhanced vegetation cover, which supports observations reported by Hughes (1995).

Commonly, flood flows move down the channel network as a flood wave, moving over a bed that is either initially dry or has a small initial flow. Hydrographs are typically characterised by extremely rapid rise times, of as little as 15-30 minutes. However, losses from the flood hydrograph through bed infiltration are an important factor in reducing the flood volume as the flood moves downstream. These transmission losses dissipate the flood, and obscure the interpretation of observed hydrographs. It is not uncommon for no flood to be observed at a gauging station, when further upstream a flood has been generated and lost to bed infiltration.

As noted above, the spotty spatial rainfall patterns observed in Arizona and Saudi Arabia are extremely difficult, if not impossible, to quantify using conventional densities of raingauge network. This, taken in conjunction with the flood transmission losses, means that conventional analysis of rainfall-runoff relationships is problematic, to say the least. Wheater and Brown (1989) present an analysis of Wadi Ghat, a 597 km^2 sub-catchment of Wadi Yiba, one of the Saudi Arabian basins discussed above. Areal rainfall was estimated from 5 raingauges and a classical unit hydrograph analysis was undertaken. A striking illustration of the ambiguity in observed relationships is the relationship between observed rainfall depth and runoff volume. Runoff coefficients ranged from 5.9 to 79.8%, and the greatest runoff volume was apparently generated by the smallest observed rainfall! This is purely an artefact of problems in characterising rainfall and the effects of transmission loss. Goodrich et al. (1997) show that the combined effects of limited storm areal coverage and transmission loss give important differences from more humid regions. Whereas generally basins in more humid climates show increasing linearity with increasing scale, the response of Walnut Gulch becomes more non-linear with increasing scale. It is argued that this will give significant errors in the application of rainfall depth-area-frequency relationships beyond the typical area of storm coverage, and that channel routing and transmission loss must be explicitly represented in watershed modelling.

The transmission losses from the surface water system are a major source of potential groundwater recharge. The characteristics of the resulting groundwater resource will depend on the underlying geology, but bed infiltration may generate shallow water tables, within a few metres of the surface, which can sustain supplies to nomadic people for a few months (as in the Hesse of the North of South Yemen), or recharge substantial alluvial aquifers with potential for continuous supply of major towns (as in Northern Oman and S.W. Saudi Arabia).

The balance between localised recharge from bed infiltration and diffuse recharge from rainfall infiltration of catchment soils will vary greatly depending on local circumstances. However, soil moisture data from Saudi Arabia (Macmillan, 1987) and Arizona (Liu et al., 1995), for example, show that most of the rainfall falling on soils in arid areas is subsequently lost by evaporation. Methods such as the chloride profile method (e.g. Bromley et al., 1997) and isotopic analyses (Allison and Hughes, 1978) have been used to quantify the residual percolation to groundwater in arid and semi-arid areas.

In some circumstances runoff occurs within an internal drainage basin, and fine deposits can support widespread surface ponding. A well known large-scale example is the Azraq oasis in N.E. Jordan, but small-scale features (Qaa's) are widespread in that area. Small scale examples were found in the HAPEX-Sahel study (Desconnets et al., 1997). Infiltration from these areas is in general not well understood, but may be extremely important for aquifer recharge. Desconnets et al. report aquifer recharge of between 5 and 20% of basin precipitation for valley bottom pools, depending on the distribution of annual rainfall.

Wadi bed transmission losses

Wadi bed infiltration has an important effect on flood propagation, but also provides recharge to alluvial aquifers. The balance between distributed infiltration from rainfall and wadi bed infiltration is obviously dependant on local conditions, but as noted above, distributed infiltration of catchment soils can be limited, and increased near surface soil moisture levels are subsequently depleted by evaporation. Hence wadi bed infiltration may often be the dominant process of groundwater recharge. As noted above, depending on the local hydrogeology, alluvial groundwater may be a readily accessible water resource. Quantification of transmission loss is thus important, but raises a number of difficulties.

One method of determining the hydraulic properties of the wadi alluvium is to undertake infiltration tests. Infiltrometer experiments give an indication of the saturated hydraulic conductivity of the surface, but results are, in my experience, highly variable. If an infiltration experiment is combined with measurement of the vertical distribution of moisture content, for example using a neutron probe, inverse solution of a numerical model of unsaturated flow can be used to identify the soil unsaturated hydraulic properties. This is illustrated for the Saudi Arabian Five Basins Study by Parissopoulos and Wheater (1992a).

In practice, spatial heterogeneity will introduce major difficulties to the up-scaling of point profile measurements. The presence of silt lenses within the alluvium was shown to have important effects on surface infiltration as well as sub-surface redistribution (Parissopoulos and Wheater, 1990), and sub-surface heterogeneity is difficult and expensive to characterise. In a series of two-dimensional numerical experiments it was shown that "infiltration opportunity time", i.e. the duration and spatial extent of surface wetting, was more important than high flow stage in influencing infiltration, that significant reductions in infiltration occur once hydraulic connection is made with a water table, and that hysteresis effects were generally small (Parissopoulos and Wheater, 1992b). Also sands and gravels appeared effective in restricting evaporation losses from groundwater (Parissopoulos and Wheater, 1991).

Additional process complexity arises, however. General experience from the Five Basins Study was that wadi alluvium was highly transmissive, yet observed flood propagation indicated significantly lower losses than could be inferred from in situ hydraulic properties, even allowing for sub-surface heterogeneity. Possible causes are air entrapment, which could restrict infiltration rates, and the unknown effects of bed mobilisation and possible pore blockage by the heavy sediment loads transmitted under flood flow conditions.

A commonly observed effect in the S.W. Saudi Arabian studies was that in the recession phase of the flow, deposition of a thin (1-2mm) skin of fine sediment on the wadi bed occurs, which is sufficient to sustain flow over an unsaturated and transmissive wadi bed. Once the flow has ceased, this skin dries and breaks up so that the underlying alluvium is exposed for subsequent flow events. Crerar et al., (1988) observed from laboratory experiments that a thin continuous silt layer was formed at low velocities. At higher velocities no such layer occurred, as the bed surface was mobilised, but infiltration to the bed was still apparently inhibited. It was suggested that this could be due to clogging of the top layer of sand due to silt in the infiltrating water, or formation of a silt layer below the mobile upper part of the bed.

Further evidence for the heterogeneity of observed response comes from the observations of Hughes and Sami (1992) from a 39.6 km^2 semi-arid catchment in S.Africa. Soil moisture was monitored by neutron probe following two flow events. At some locations immediate response (monitored 1 day later) occurred throughout the profile, at others, an immediate response near surface was followed by a delayed response at depth. Away from the inundated area, delayed response, assumed due to lateral subsurface transmission, occurred after 21 days.

The overall implication of the above observations is that transmission losses are complex, and it is not possible at present to extrapolate from in-situ point profile hydraulic properties to infer transmission losses from wadi channels. However, analysis of observed flood flows at different locations can allow quantification of losses, and studies by Walters (1990) and Jordan (1977), for example, provide evidence that the rate of loss is linearly related to the volume of surface discharge.

For S.W. Saudi Arabia, the following relationships were defined:

$$LOSSL = 4.56 + 0.02216\,UPSQ - 2034\,SLOPE + 7.34\,ANTEC$$

(s.e. 4.15)

$$LOSSL = 3.75 \times 10^{-5}\,UPSQ^{0.821}\,SLOPE^{-0.865}\,ACWW^{0.497}$$

(s.e. 0.146 log units (±34%))

$$LOSSL = 5.7 \times 10^{-5}\,UPSQ^{0.968}\,SLOPE^{-1.049}$$

(s.e. 0.184 loge units (±44%))

where:-

LOSSL	=	Transmission loss rate (1000m^3/km) (O.R.1.08-87.9)
UPSQ	=	Upstream hydrograph volume (1000m^3) (O.R. 69-3744)
SLOPE	=	Slope of reach (m/m) (O.R.0.001-0.011)
ANTEC	=	Antecedent moisture index (O.R. 0.10-1.00)
ACWW	=	Active channel width (m) (O.R. 25-231)
and O.R.	=	Observed range

However, generalisation from limited experience can be misleading. Wheater et al. (1997) analysed transmission losses between 2 pairs of flow gauges on the Walnut Gulch catchment for a ten year sequence and found that the simple linear model of transmission loss as proportional to upstream flow was inadequate, suggesting that available bed storage was a limiting factor. The role of available storage was also discussed by Telvari et al. (1998), with reference to the Fowler's Gap catchment in Australia. Runoff plots were used to estimate runoff production as overland flow for a 4km^2 basin. It was inferred that 7000 m^3 of overland flow becomes transmission loss and that once this alluvial storage is satisfied, approximately two-thirds of overland flow is transmitted downstream.

A similar concept was developed by Andersen et al. (1998) at larger scale for the sand rivers of Botswana, which have alluvial beds of 20-200m width and 2-20m depth. Detailed observations of water table response showed that a single major event after a seven weeks dry period was sufficient to fully satisfy available alluvial storage (the river bed reached full saturation within 10 hours). No significant drawdown occurred between subsequent events and significant resource potential remained throughout the dry season. It was suggested that two sources of transmission loss could be occurring, direct losses to the bed, limited by available storage, and losses through the banks during flood events.

It can be concluded that transmission loss is complex, that where deep unsaturated alluvial deposits exist the simple linear model as developed by Jordan (1977) and implicit in the results of Walters (1990) may be applicable, but that where alluvial storage is limited, this must be taken into account.

Groundwater recharge from ephemeral flows

The relationship between wadi flow transmission losses and groundwater recharge will depend on the underlying geology. The effect of lenses of reduced permeability on the infiltration process has been discussed and illustrated above, but once infiltration has taken place, the alluvium underlying the wadi bed is effective in minimising evaporation loss through capillary rise (the coarse structure of alluvial deposits minimises capillary effects). Thus Hellwig (1973), for example, found that dropping the water table below 60cm in sand with a mean diameter of 0.53mm effectively prevented evaporation losses, and Sorey and Matlock (1969) reported that measured evaporation rates from streambed sand were lower than those reported for irrigated soils.

Parrisopoulos and Wheater (1991) combined two-dimensional simulation of unsaturated wadi-bed response with Deardorff's (1977) empirical model of bare soil evaporation to show that evaporation losses were not in general significant for the water balance or water table response in short-term simulation (i.e. for periods up to 10 days). However, the influence of vapour diffusion was not explicitly represented, and long term losses are not well understood. Andersen et al. (1998) show that losses are high when the alluvial aquifer is fully saturated, but are small once the water table drops below the surface.

Sorman and Abdulrazzak (1993) provided an analysis of groundwater rise due to transmission loss for an experimental reach in Wadi Tabalah, S.W. Saudi Arabia and estimated that on average 75% of bed infiltration reaches the water table. There is in general little information available to relate flood transmission loss to groundwater recharge, however. The differences between the two are expected to be small, but will depend on residual moisture stored in the unsaturated zone and its subsequent drying characteristics. But if water tables approach the surface, relatively large evaporation losses may occur.

Again, it is tempting to draw over-general conclusions from limited data. In the study of the sand-rivers of Botswana, referred to above, it was expected that recharge of the alluvial river beds would involve complex unsaturated zone response. In fact, observations showed that the first flood of the wet season was sufficient to fully recharge the alluvial river bed aquifer. This storage was topped up in subsequent floods, and depleted by evaporation when the water table was near-surface, but in many sections sufficient water remained throughout the dry season to provide adequate sustainable water supplies for rural villages. And as noted above, Wheater et al. (1997)

showed for Walnut Gulch and Telvari et al. (1998) for Fraser's Gap that limited river bed storage affected transmission loss. It is evident that surface water/groundwater interactions depend strongly on the local characteristics of the underlying alluvium and the extent of their connection to, or isolation from, other aquifer systems.

Very recent work at Walnut Gulch (Goodrich et al., 2004) has investigated ephemeral channel recharge using a range of experimental methods, combined with modelling. These included a reach water balance method, including estimates of near channel evapotranspiration losses, geochemical methods, analysis of changes in groundwater levels and microgravity measurements, and unsaturated zone flow and temperature analyses. The conclusions were that ephemeral channel losses were significant as an input to the underlying regional aquifer, and that the range of methods for recharge estimation agreed within a factor of three (reach water balance methods giving the higher estimates).

An important requirement for recharge estimation has arisen in connection with the proposal for a repository for high level nuclear waste at Yucca Mountain, Nevada. Flint et al. (2002) reviewed a wide range of methods, including analysis of physical data from unsaturated zone profiles of moisture and heat, environmental tracers, and watershed modelling. The results indicate extreme variability in space and time, with watershed modelling giving a range from zero to several hundred mm/year, depending on spatial location. The high values arise due to flow focussing in ephemeral channels, and subsequent channel bed infiltration.

HYDROLOGICAL MODELLING AND THE REPRESENTATION OF RAINFALL

The preceding discussion illustrates some of the particular characteristics of arid areas which place special requirements on hydrological modelling, for example for flood management or water resources evaluation. One particular area of difficulty is rainfall, especially where convective storms are an important influence. The work of Michaud and Sorooshian (1994) demonstrated the sensitivity of flood peak simulation to the spatial resolution of rainfall input. This obviously has disturbing implications for flood modelling, particularly where data availability is limited to conventional raingauge densities. Indeed, it appears highly unlikely that suitable raingauge densities will ever be practicable for routine monitoring. However, the availability of 2km resolution radar data in the USA can provide adequate information and a radar could be installed elsewhere for particular applications. Morin et al. (1995) report results from a radar located in the Middle East, for example.

One way forward is to develop an understanding of the properties of spatial rainfall based on high density experimental networks and/or radar data, and represent those properties statistically within a spatial rainfall model for more general application. It is likely that this would have to be done within a stochastic modelling framework in which equally-likely realisations of spatial rainfall are produced, conditioned by available data. Some simple empirical first steps in this direction were taken by Wheater et al. (1991a,b) for S.W.Saudi Arabia and Wheater et al. (1995) for Oman. In the Saudi Arabian studies, as noted earlier, raingauge data was available at approximately 10km spacing and spatial correlation was low. Hence a multi-variate model was developed, assuming independence of raingauge rainfall. Based on observed distributions, seasonally-dependent catchment rainday occurrence was simulated, dependent on whether the preceding day was wet or dry. The number of gauges experiencing rainfall was then sampled, and the locations selected based on observed occurrences (this allowed for increased frequency of raindays with increased elevation). Finally, start-times, durations and hourly intensities were generated. Model performance was compared with observations. Rainfall from random selections of raingauges was well reproduced, but when clusters of adjacent gauges were evaluated, a degree of spatial organisation of occurrence was observed, but not simulated. It was evident that a weak degree of correlation was present, which should not be neglected. Hence in extension of this approach to Oman (Wheater et al., 1995), observed spatial distributions were sampled, with satisfactory results.

However, this multi-variate approach suffers from limitations of raingauge density, and in general a model in continuous space (and continuous time) is desirable. A family of stochastic rainfall models of point rainfall was proposed by Rodriguez-Iturbe, Cox and Isham (1987, 1988) and applied to UK rainfall by Onof and Wheater (1993, 1994). The basic concept is that a Poisson process is used to generate the arrival of storms. Associated with a storm is the arrival of raincells, of uniform intensity for a given duration (sampled from specified distributions). The overlapping of these rectangular pulse cells generates the storm intensity profile in time. These models were shown to have generally good performance for the UK in reproducing rainfall properties at different time-scales (from hourly upwards), and extreme values.

Cox and Isham (1988) extended this concept to a model in space and time, whereby the raincells are circular and arrive in space within a storm region. As before, the overlapping of cells produces a complex rainfall intensity profile, now in space as well as time. This model has been developed further by Northrop (1998) to include elliptical cells and storms and is being applied to UK rainfall (Northrop et al., 1999).

Recent work (Samuel, 1999) has been exploring the capability of these models to reproduce the convective rainfall of Walnut Gulch. Although work with the spatial-temporal model is still at a preliminary stage, the results are encouraging, and there is promise with this approach to address the significant problems of spatial representation for hydrological modelling.

INTEGRATED MODELLING FOR WATER RESOURCE EVALUATION

Appropriate strategies for water resource development must recognise the essential physical characteristics of the hydrological processes. Surface water storage, although subject to high evaporation losses, is widely used, although temporal variability of flows must be adequately represented to define long term yields. It can be noted that in some regions, for example, the northern areas of southern Yemen, small scale storage has been developed as an appropriate method to maximise the available resource from spatially-localised rainfall. Numbers of small storages have been developed, some of which will fill when localised rainfall occurs. These then provide a short-term resource for a nomadic family and its livestock.

Groundwater is a resource particularly well suited to arid regions. Subsurface storage minimises evaporation loss and can provide long-term yields from infrequent recharge events. The recharge of alluvial groundwater systems by ephemeral flows can provide an appropriate resource; this has been widely recognised by traditional development, such as the "afalaj" of Oman and elsewhere. There may, however, be opportunities for augmenting recharge and more effectively managing these groundwater systems. In any case, it is essential to quantify the sustainable yield of such systems, for appropriate resource development. This is extremely difficult, and requires careful analysis and interpretation of surface and subsurface responses, based on available observed data. It has been seen that observations of surface flow may not define the available resource, and similarly observed groundwater response does not necessarily indicate upstream recharge. In addition, records of surface flows and groundwater levels, coupled with ill-defined histories of abstraction, are generally insufficient to define long term variability of the available resource.

To capture the variability of rainfall and the effects of transmission loss on surface flows, a distributed modelling approach is necessary. If groundwater is to be included, integrated modelling of surface water and groundwater is needed. This raises issues of the availability of suitable models. Few surface water models can explicitly represent the key features of wadi systems. Available distributed surface water models specifically designed for arid areas include KINEROS (Wheater and Bell, 1983, Michaud and Sorooshian, 1994) and the model of Sharma (1997, 1998). KINEROS is readily available (Semmens et al., 2005), but currently for event-based rather than continuous simulation, and has mainly been applied to small catchments. Most water resource applications, e.g. in Africa (Hughes, 2005) and Australia (Croke and Jakeman, 2005), have used models that do not explicitly include transmission loss processes. For integrated modelling of surface and groundwater the problems are greater. Most surface water models have at best a crude representation of groundwater (typically as a single lumped groundwater store). Conversely, most groundwater models cannot represent the surface hydrology and channel bed interactions that are of fundamental importance to recharge estimation in wadi systems.

In an attempt to address these problems, a distributed approach to the integrated modelling of the surface and groundwater response of wadi systems was developed by Wheater et al. (1995) (Figure 3). This requires the characterisation of the spatial and temporal variability of rainfall, distributed infiltration, runoff generation and flow transmission losses, and the ensuing groundwater recharge and groundwater response. This presents some technical difficulties, although the integration of surface and groundwater modelling allows maximum use to be made of available information, so that, for example, groundwater response can feed back information to constrain surface hydrological parameterisation. It does, however, provide the only feasible method of exploring the internal response of a catchment to management options.

In a recent application, this integrated modelling approach was developed for Wadi Ghulaji, Sultanate of Oman, to evaluate options for groundwater recharge management (Wheater et al., 1995). Proposals to be evaluated included recharge dams to attenuate surface flows and provide managed groundwater recharge in key locations. The modelling framework involved the coupling of a distributed rainfall model, a distributed water balance model (incorporating rainfall-runoff processes, soil infiltration and wadi flow transmission losses), and a distributed groundwater model.

The representation of rainfall spatial variability presents technical difficulties, since data are limited. Detailed analysis was undertaken of 19 rain gauges in the Sharqiyah region, and of six raingauges in the catchment itself. A stochastic multi-variate temporal-spatial model was devised for daily rainfall, a modified version of a scheme originally developed by Wheater et al., 1991a, b. The occurrence of catchment rainfall was determined according to a seasonally-variable first order Markov process, conditioned on rainfall occurrence from the previous day. The number and locations of active raingauges and the gauge depths were derived by random sampling from observed distributions.

The distributed water resource model represents the catchment as a network of two-dimensional plane and linear channel elements. Runoff and infiltration from the planes was simulated using the SCS approach. Wadi flows incorporate a linear transmission loss algorithm based on work by Jordan (1977) and Walters (1990). Finally, a groundwater model was developed based on a detailed hydrogeological investigation which led to a multi-layer representation of uncemented gravels, weakly/strongly cemented gravels and strongly cemented/fissured gravel/bedrock, using MODFLOW.

The model was calibrated to the limited flow data available (a single event) (Figure 4), and was able to reproduce the distribution of runoff and groundwater recharge within the catchment through a rational association on loss parameters with topography, geology and wadi characteristics. Extended synthetic data sequences were then run to investigate catchment water balances under scenarios of different runoff exceedance probabilities, and to investigate management options.

CONCLUSIONS

It has been shown that for many applications, the hydrological characteristics of arid areas present severe problems for conventional methods of analysis. Recent data provide new insights that can be used as the basis for development of more appropriate methods for flood design and water resource evaluation, and in turn, to define data needs and research priorities. Intensive high quality research is needed, particularly to investigate processes such as spatial rainfall, and infiltration and groundwater recharge from ephemeral flows.

For water resource management to maximise the resource potential, define long-term sustainable yields and protect traditional sources, it is argued that distributed modelling is a valuable, if not an essential tool. However, this confronts severe problems of characterisation of rainfall, rainfall-runoff processes, and groundwater recharge, and of understanding the detailed hydrogeological response of what are often complex groundwater systems. Similarly, new approaches to flood design and management are required which represent the extreme value characteristics of arid areas and recognise the severe problems of conventional rainfall-runoff analysis.

Above all, basic requirements are for high quality data of rainfall, surface water flows and groundwater response to support regional analyses and the development of appropriate methodologies. Too often, studies focus on either surface or subsurface response without taking an integrated view. Too often, networks are reduced after a few years without recognition that the essential variability of wadi response can only be characterised by relatively long records. Quality control of data is vital, but can easily be lost sight of with ready access to computerised data-bases.

Superimposed on these basic data needs are the requirement for specific research studies to develop scientific understanding of processes, including sediment transport, surface water/groundwater interactions in the active wadi channel, evaporation processes and consumptive use of wadi vegetation, and the wider issues of groundwater recharge. These are challenging studies, and require the full range of advanced hydrological experimental methods to be applied, particularly integrating quantity and quality data to deduce system responses, and making full use of remote sensing and geophysical methods to characterise system properties.

Building on these studies, research is urgently needed into the development and application of models suitable for decision support application in arid areas. The paper presents some proposed ways forward. This research can be greatly assisted by the sharing of experience, through model evaluation and intercomparison, and the sharing of data to facilitate this.

A POSTSCRIPT – GWADI: Water and Development Information for Arid Lands – a Global Network

In an attempt to promote the development and sharing of state-of-the-art knowledge about water resource management in arid areas, UNESCO has developed a global Wadi programme, GWADI. The special problems of hydrological modelling for arid areas were addressed at an international workshop in Roorkee, India, earlier this year. The world's leading international experts on modelling arid zone systems provided a set of lectures that can be accessed through the GWADI web-site http://www.gwadi.org/, with web-links to associated software. Future activities depend on funding, but it is hoped to develop a shared data resource and model intercomparison studies, and to promote the exchange of information among the global community.

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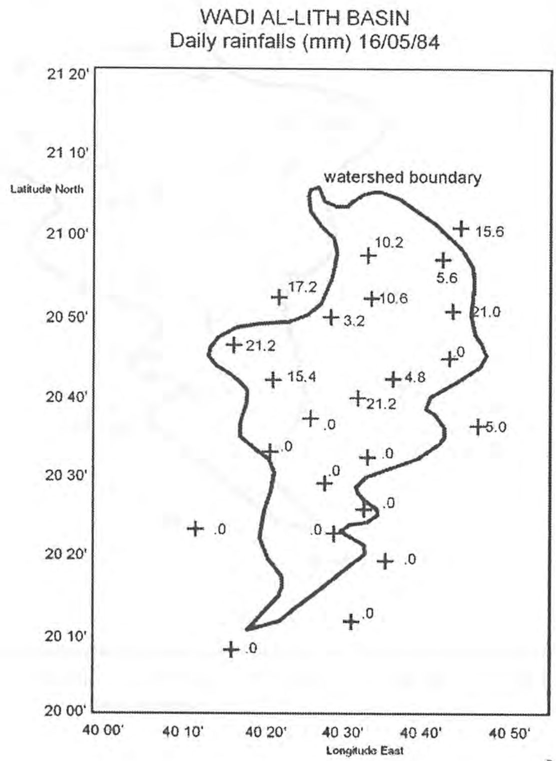

Figure 1 Wadi Al-Lith daily rainfall, 16th May 1994

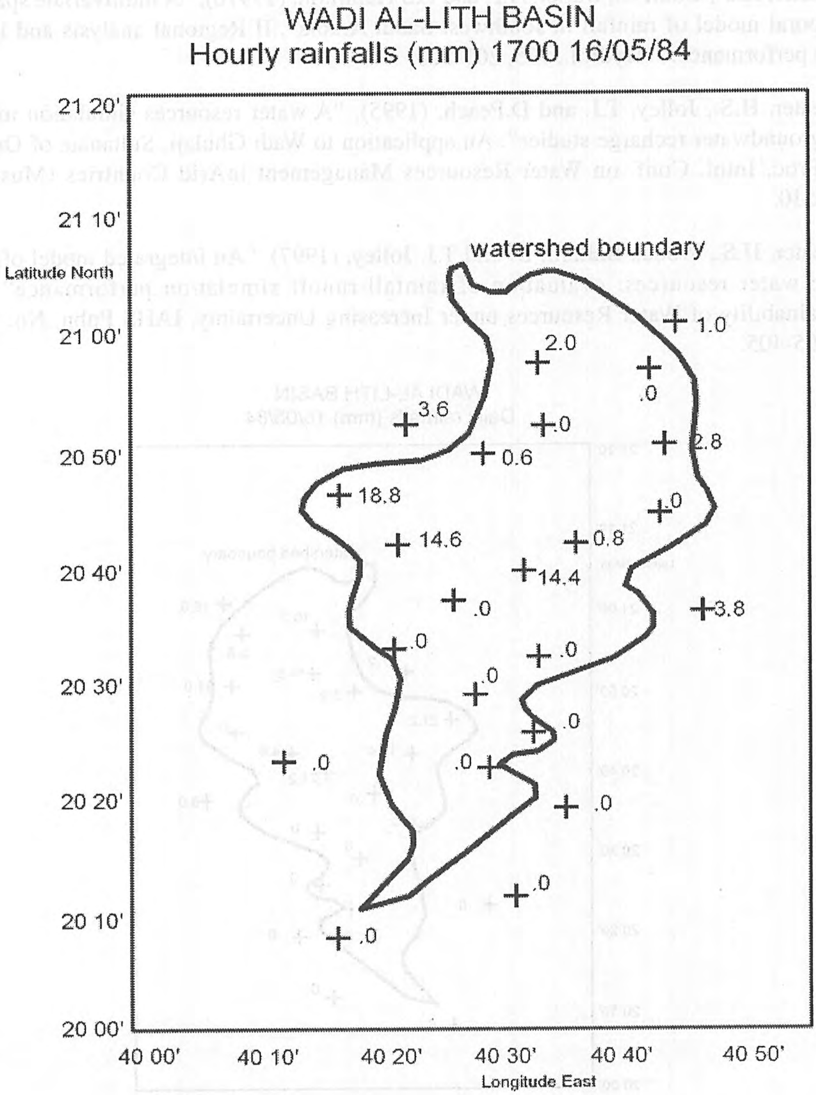

Figure 2 Wadi Al-Lith hourly rainfall, 16th May 1994

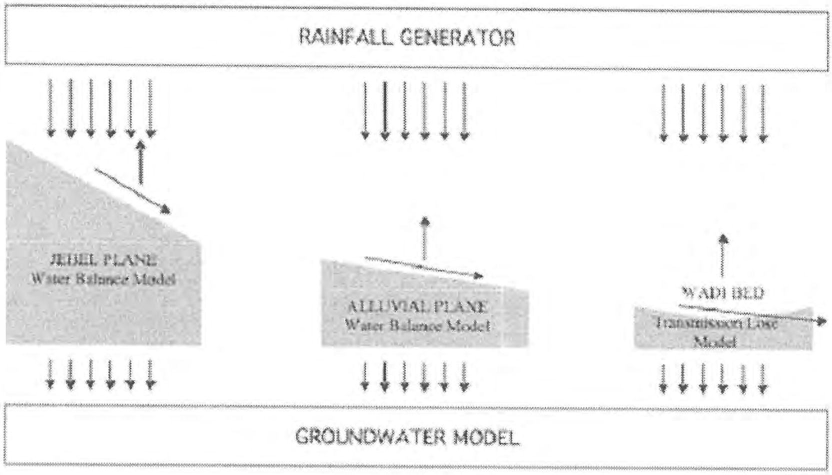

Figure 3 Schematic of distributed wadi water resource model

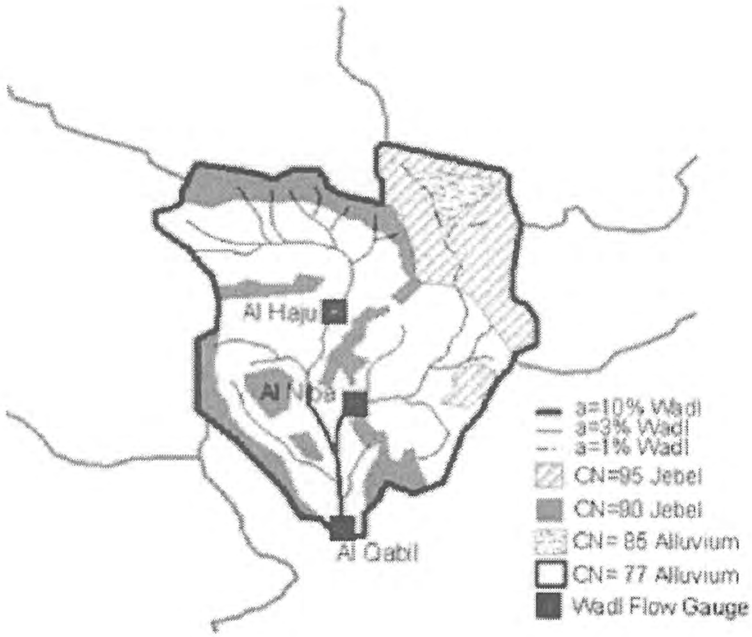

Figure 4 Distributed parameters for wadi water resource model, Wadi Ghulaji, Sultanate of Oman

Comparing Eddy Covariance and Soil Water Balance Methods for Evapotranspiration Measurement in Palmyraoasis

Ihad Jnad, Jean Pierre BRUNEL, Abdullah Droubi

COMPARING EDDY COVARIANCE AND SOIL WATER BALANCE METHODS FOR EVAPO-TRANSPIRATION MEASUREMENT IN PALMYRA OASIS

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ABSTRACT

In this study eddy covariance method results for daily evapotranspiration (ET_{eddy}) in the Palmyra Oasis were compared with those obtained from the water balance method (ET_{bal}). The eddy covariance measurements were made with a 3D sonic anemometer and a Krypton hygrometer. Evapotranspiration estimated by the water balance method was determined using a TDR for soil moisture measurement and a tensiometer for matric potential measurement. A total of 9 pairs of ET_{eddy} and ET_{bal} daily values were compared. Good agreements were found between the two tested methods with a RMSE of 15.

Keywords: Evapotranspiration, Eddy covariance, Oasis, Soil water balance

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Introduction

Oases are prominent features within arid and semi-arid areas. They provide important economical, recreational and natural resources. Water resources in arid and semi arid areas are commonly scarce and in great demand especially in the agricultural sector where about 80% of the available water resources are used. Reliable estimates of evapotranspiration (ET) in an oasis are needed to increase water use efficiency and provide better management of available water resources. Oases typically have a mixture of trees with different intercrops. This results in difficulties in estimating ET in the oasis. Currently evapotranspiration from the oasis is predicted using weather based equations such as Penman, Penman Monteith, and Blaney-Criddle equations. Climatic equations perform well over uniform vegetation; but it is not known how accurate this equation will predict ET of sites that differs from sites for which the equation has been calibrated with respect to soil, climate, and vegetation. Calibration of these equations is usually achieved using crop coefficients. Unfortunately crop coefficients for a mixture of crops are not easily obtained and only an approximate method to determine it is available (Allen et al. 1998) Alternative methods to determine actual evapotranspiration are weighing lysimeters, soil water balance, and micrometeorological methods.

The weighing lysimeter is one of the most popular methods used to estimate actual evapotranspiration. However, this method is limited in that lysimeters are costly, non-portable, and difficult to establish (Kizer et al., 1990). The soil water balance is an accurate method and it has been used in many studies for ET determination (Gunston and Batchelor, 1983) but it is limited by the difficulty of determining deep percolation from the crop root zone (Ward and Robinson, 1990). Micrometeorological techniques such as eddy covariance (Swinbank, 1951) can be used to measure actual ET by correlating fluctuations of vertical wind speed with fluctuations of vapor density. This method has a major advantage that it can be applied for determining actual ET without need for calibration .

Samaan et al. 2005 compared ET values from the Palmyra Oasis (in Syria) measured using eddy covariance techniques with that calculated by Penman, Penman Monteith, and Blaney-Criddle equations during the years of 2003 and 2004. They used a method suggested by Allen et al. 1998 for obtaining crop coefficients for mixed crops. They found that ET estimation from climatic equations was considerably higher than that measured using eddy covariance method (Table 1). It was not clear if this deviation between results is due to use of an inappropriate crop coefficient or because the eddy covariance method underestimated ET. (Leuning and King, 1992; Schellekens, 2000) reported that micrometeorological methods may lead to underestimation of evapotranspiration.

Table 1: Comparison of annual ET (mm) measured with eddy covariance method with that calculated with climatic equation in the Palmyra Oasis (Samman et al., 2005)

Year	Eddy covariance	Blaney-Criddle	Penman	Penman- Monteith
2002	807	1340	1221	1210
2003	742	1360	1196	1174

There were several studies to compare the eddy covariance method with the Bowen ratio method (Lang et al., 1983, Tanner, 1988, Dugas et al., 1991), both methods are micrometeorological. The objective of this study was to compare the performance of the eddy covariance method for ET measurements in the Palmyra Oasis with the independent soil water balance method.

Study area

The study area is located in the Palmyra Oasis near the town of Palmyra (latitude 34ˈ 32ó N, longitude 38ˈ 16ó E) in the center of the Syrian Desert. The climate is Mediterranean arid. The average maximum temperature during the hottest month is 37.8 Cˈ and the average minimum temperature during the coldest month is 2.4 Cˈ. The rainy season extends from October until May with an average annual rainfall of 120 mm. Figure 1 shows rainfall distribution during the year of 2004. The estimated annual potential evapotranspiration is 1760 mm and the pan evaporation is 2300 mm. The whole Oasis covers 1000 ha. The main cultivations are olive trees (250,000 trees), palm trees (70,000 trees), pomegranate trees (80,000 trees), and other fruit trees (250,000). The micrometeorological and soil moisture measurements were made in a 0.4 ha field chosen to be a good representative with a fetch of around 1 km in every direction.

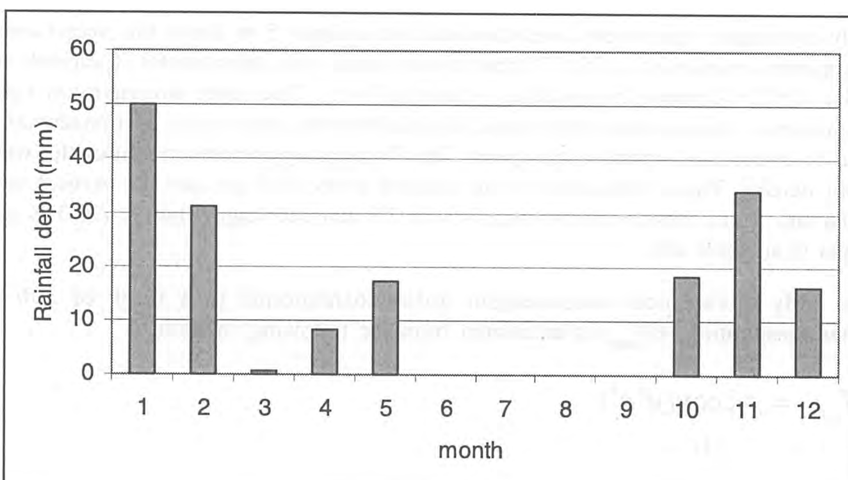

Figure 1: Rainfall distribution during year of 2004

The soil texture is sandy loam to a depth of 0.35 m and sandy clay loam between 0.35 m and 1.50 m below the soil surface. The corresponding soil bulk densities for each depth are 1.39 and 1.2 g/ cm^3, respectively. The oasis is irrigated with a traditional flood irrigation method. Water is delivered to the farmer once a month from a governmental public well. However, some farmers have their own wells and they apply additional irrigation to their farm land. Table 2 presents the irrigation schedule and amount of irrigation during the year of 2004 applied to the 0.4 ha field in which the instruments were installed.

Table 2: Applied irrigation water during year of 2004 to the o.4 ha field in which the instruments for ET measurements were installed

Date	Total applied volume (m3)	Type of well
30-Mar	259.2	G[1]
17-Apr	217.9	G
18-May	214.1	G
28-May	284.2	P[2]
08-Jun	199.4	G
28-Jun	289.1	P
10-Jul	210.5	G
26-Jul	290.0	P
10-Aug	210.5	G
29-Aug	304.6	P
10-Sep	188.6	G
30-Sep	224.3	P
11-Oct	204.2	G
28-Dec	174.9	P

[1] Governmental well, [2] private well

Materials and methods

Eddy covariance measurements

Eddy covariance instruments were mounted on a tower 5 m above the trees canopy. The system consists of a CSAT3 three dimensional sonic anemometer (Campbell sc.) and a KH20 Krypton hygrometer (Campbell sc.). The three dimensional sonic anemometer which pulses ultra sonic signals between three pairs of transducers is used to determine vertical wind speed. The Krypton hygrometer measures the water vapor density. These instruments were scanned every 0.15 sec and the vertical wind speed and vapor pressure are averaged every 15 min and logged into a CR23 X data logger (Campbell sc.).

The eddy covariance measurement point corresponds to a fetch of 200 m. Evapotranspiration (ET_{eddy}) is calculated from the following equation:

$$ET_{eddy} = \rho \lambda \operatorname{cov}(w'q') \quad (1)$$

where

ET_{eddy}: *is the e*vapotranspiration calculated by the eddy covariance method (mm/day)

ë is the latent heat of vaporization of water

ρ is the density of air

w' is the deviation in vertical wind speed from the average vertical wind speed

q' is the deviation in specific humidity of air from the average specific humidity of air

During the year of 2004, eddy covariance measurements were made over the tree canopy in the Oasis from January 1 until November 25.

Water balance method

In the same field the eddy covariance system was installed, seven 30 cm TDR probes (CS616, Campbell Sc.) were used to measure volumetric moisture content. The probes were installed horizontally at depths of 0.1, 0.25, 0.5, 0.75, 1, 1.25, and 1.50 m below the soil surface. The TDR probes were connected to a CR10X data logger (Campbell Sc.) and soil moisture measurements were recorded every hour. Soil matric potential was measured with a mercury tensiometer (STM 2150, SDEC FRANCE). Seven tensiometers were installed at similar depths as the TDR probes. The tensiometers readings were taken manually on a daily basis.

Ignoring lateral movement of water, the water balance equation was written for the upper 1.5 m of the root zone (considered as control volume) as follows. The tensiometers were serviced once a week during dry season.

$$0 = P + I - ET_{bal.} - F \pm \Delta S \qquad (2)$$

where,
P is precipitation
I is irrigation
F is the downward flux of soil water at the lower boundary of the control volume
$ET_{bal.}$ is the evapotranspiration calculated from the water balance method.
"S is the change in stored soil water which is determined by multiplying the change in volumetric water content by the depth of soil layer.

Groundwater at the site is deeper than 10 m therefore upward movement of soil water into the control volume was neglected. To eliminate P, Eq. 2 will be applied in the dry season only which extends from end of May until mid October. Moreover, to eliminate I, Eq. 2 will be applied in the period between irrigations only. The downward flux from the lower boundary of the control volume is estimated by applying Darcy's Law between two points located at Z_1=1.25 m and at Z_2=1.5 m below the soil surface as follows :

$$Jw = -k(h)\frac{\Delta h}{\Delta z} \qquad (3)$$

where
$k(h)$ is the hydraulic conductivity
Jw is the vertical soil water flux
$\Delta h = h_{1.25} - h_{1.5}$. $h_{1.25}$ and $h_{1.25}$ are the matric potentials measured at 1.25 m and 1.5 below the soil surface, respectively.
Δz is the vertical distance between z_1 and z_2 i.e $\Delta z = 1.5 - 1.25 = 0.25\ m$

The downward soil water flux from the control volume will be omitted when Δh is negative, therefore comparison between ET_{eddy} and ET_{bal} was limited to days when $\Delta h \leq 0$
The agreement between values of ET from the eddy covariance and those from the soil water balance were quantified using the root mean square error (RMSE) as a statistical measure of goodness of fit (Loague and Green, 1991):

$$\text{RMSE} = \left[\frac{\sum (P_i - O_i)^2}{N} \right]^{0.5} \times \frac{100}{\overline{O}} \qquad (4)$$

where, P_i are values of ET_{eddy}, O_i are values of ET_{bal}, $\overline{O}$ is the mean value of ET_{bal}, and N is the number of observations. RMSE is a measure of the deviation between ET_{eddy} and ET_{bal}. Ideally it should be equal to zero.

Results and discussions

Eddy covariance measurements

Figure 2 shows values of the eddy covariance measurements of evapotranspiration (ET_{eddy}) during the year of 2004. Values of ET_{eddy} ranged from 0.63 mm /day on January 14, to 5.45 mm/day on July 12 with the total evapotranspiration during the year of 2004 equal to 675 mm. This result is similar to that obtained by Samman et. al (2005) (Table 1) .

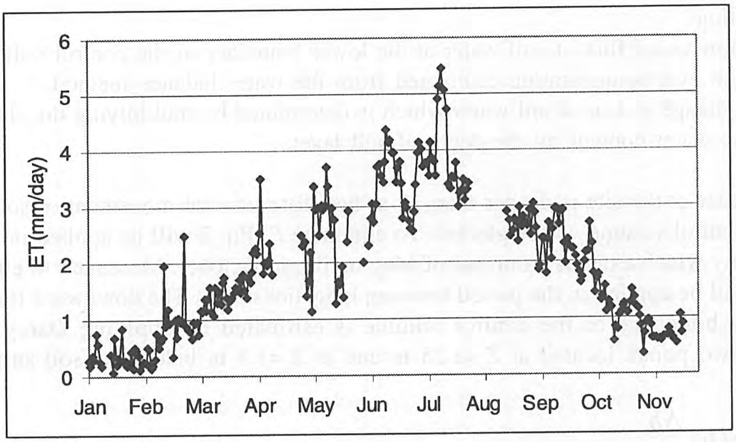

Figure 2: Values of Evapotranspiration in the Palmyra Oasis measured with the eddy covariance method during the year of 2004

Water balance measurements

As mentioned earlier, comparison of ET_{eddy} with evapotranspiration values obtained from the soil water balance method (ET_{bal}) were limited to periods when the downwards soil water flux from the lower boundary of the control volume (top 1.5 m in this study) is zero (i.e. $\Delta h \leq 0$). Figure 3 shows the variation of Δh values as measured with tensiometers between May 20 and October 15. There were four periods when Δh was negative: 7 to 9 of July, 23 to 27 of July, 8 to 10 of

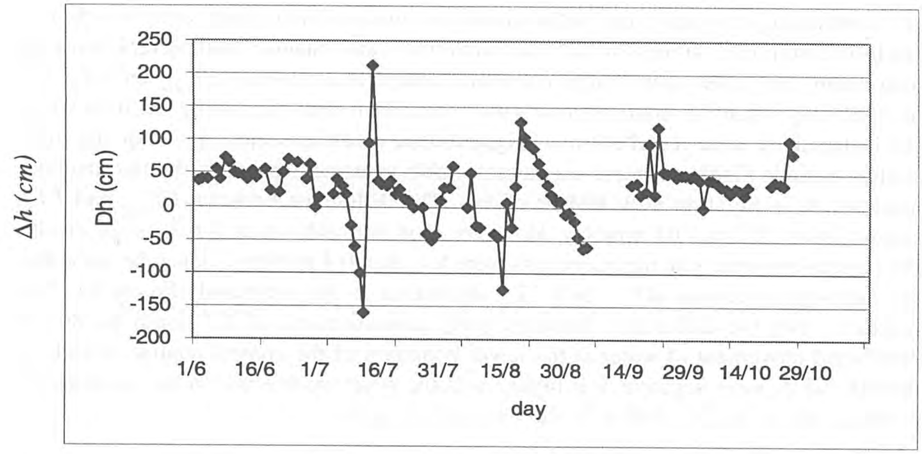

Figure 3: Daily Δh ($\Delta h = h_{1.25} - h_{1.5}$) values between May 30 and October 15.

Table 3 shows an example of the ET_{bal} calculation on August 26. On that day, P, I, and F were equal to zero. Therefore Eq. 2 is reduced to

$$ET_{bal.} = \Delta S \quad (4)$$

It can be seen from Table 3 that more than 70 % of ET_{bal} occurred from the top 50 cm of the soil profile, this indicates that the major root mass is concentrated at this depth.

Table 3: Example of daily ET calculation using soil water balance method on August 26.

Depth Of TDR probs (cm)	Θ_1[a]	Θ_2[b]	Δθ	ΔZ[c] (m)	ΔS[d] (m)	ΔET[e] (mm)	Cum. ET (mm)	ΔET/ET× 100
10	14.061	13.625	0.436	0.225	0.098	0.981	0.981	32.0
25	14.235	13.943	0.292	0.250	0.073	0.730	1.711	55.8
50	15.800	15.604	0.197	0.250	0.049	0.492	2.203	71.9
75	22.985	22.862	0.123	0.250	0.031	0.308	2.511	81.9
100	21.213	21.115	0.098	0.250	0.025	0.246	2.757	90.0
125	19.565	19.491	0.074	0.250	0.018	0.185	2.941	96.0
150	19.589	19.540	0.049	0.250	0.012	0.123	3.064	100.0

[a]volumetric moisture content at the beginning of the day, [b] volumetric water content at the end of the day, [c] thickness of soil layer, [d]the change in stored soil water, [e] evapotranspiration from each soil layer, cumulative evapotranspiration

Comparing ET_{eddy} with ET_{bal}.

Table 4 compares values of ET_{eddy} with ET_{bal} for three periods. For the period of 7 to 9 of July, there were large differences between ET_{eddy} and ET_{bal} values with the error ranging from 40 to 48 %. The difference between the two methods occurred because the field where the instruments were installed was irrigated on 28th of June from a private well (Table 2) while other fields in the Oasis were not irrigated.

As mentioned previously, the eddy covariance measurement point corresponds to a fetch of 200 m (i.e. an area of 12.5 ha) while the water balance method represents the area nearby the TDR probes only. Therefore, comparison between ET_{eddy} and ET_{bal} will be valid only when the fields located within the 200 m fetch (including the field where the instruments were installed) are irrigated almost at the same time. For the other studied periods (Table 4), there was a reasonable agreement between the two methods used for *ET* estimation with RMSE of 15. The difference between ET_{eddy} and ET_{bal} ranged from 0.01 to 1.03 mm/day. However, it is noticeable that for Ä*h* <*-20* cm the differences between both measurements were less than 0.4 mm/day. Generally speaking, the difference between ET_{eddy} and ET_{bal} decreased as Ä*h* increased (Figure 4). This indicates that the difference between both measurements of *ET* could be due to downward movement of water at the lower boundary of the control volume in spite of that Ä*h* values were negative. It is highly possible to get small errors in the tensiometers readings due to the air bubble in the tensiometer water.

Another source of deviation between the two measurements is the large difference in the size of the representative area for each of the studied methods (12.5 ha for the eddy covariance method compared to a few square meters for the water balance method). In fact there is some lag time (less than 12 hr) in irrigation schedule for fields located within a 200 m fetch of eddy covariance measurement points.

Table 4: Comparison of ET_{eddy} with ET_{bal}

Date	Δh (cm)	ET_{eddy} (mm/day)	ET_{ba} (mm/day)	ET_{eddy}- ET_{ba}	% Error
July-7	-28	4.13	7.85	-3.72	-47.35
July-8	-60	3.86	7.44	-3.57	-48.04
July-9	-100	3.79	6.40	-2.61	-40.81
July-23	0	3.21	4.10	-0.89	-21.81
July-24	-40	3.25	3.43	-0.18	-5.10
July-26	-50	3.47	3.25	0.22	6.90
July-27	-44	3.11	3.12	-0.01	-0.46
Aug.-24	-10	2.37	3.40	-1.03	-30.31
Aug.-25	-8	2.97	3.31	-0.34	-10.20
Aug.-26	-22	2.63	3.00	-0.37	-12.28
Aug.-27	-46	2.81	2.88	-0.07	-2.51
Aug.-28	-64	2.70	2.64	0.06	2.19

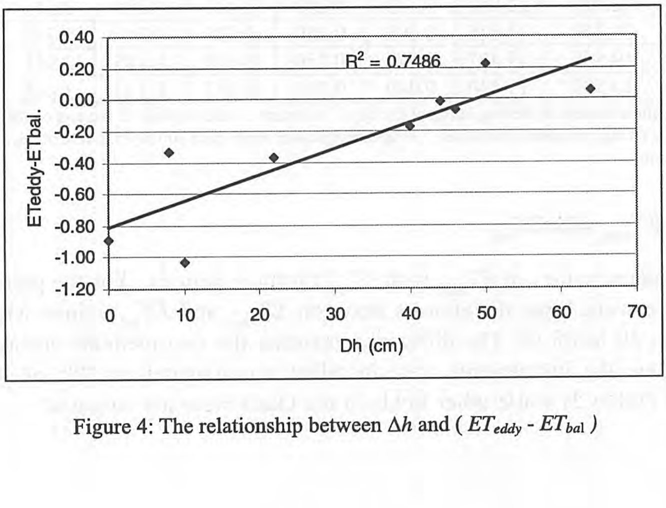

Figure 4: The relationship between Δh and (ET_{eddy} - ET_{bal})

Summary and Conclusion

ET values measured with the eddy covariance method in the Palmyra Oasis were checked against values of *ET* measured with the soil budget method. Reasonable agreements between both evaluated methods were obtained when the conditions of the comparison were met (similar irrigation schedule, no downward movement of water at the lower boundary of the control volume). Therefore the eddy covariance could be used to obtain an accurate measurement of ET in oases systems and it can be used for local calibration of the climatic equations used for ET estimation.

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Water Conservation and Management in an Extreme Arid Area of Pakistan

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WATER CONSERVATION AND MANAGEMENT IN AN EXTREME ARID AREA OF PAKISTAN

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ABSTRACT

About 70 million hectares of Pakistan fall under an arid and semi-arid climate, including desert land. Cholistan is one of the main deserts consisting of 2.6 million hectares where water scarcity is the fundamental problem for the human and livestock population because most of the groundwater is highly saline. Rainfall is a major freshwater source, which occurs mostly during the monsoon season (July to September). Therefore, water conservation and management in the desert has crucial importance. The Pakistan Council of Research in Water Resources (PCRWR) has been conducting research studies on rainwater harvesting since 1989 in the Cholistan Desert by developing catchment through various techniques and constructing ponds with different storage capacities ranging between 3000 and 15000 m^3. These ponds have been designed to collect maximum rainwater within the shortest possible time and to minimize seepage and evaporation losses. As a result of successful field research on rainwater harvesting systems, PCRWR has initiated a large research and development programme, covering the entire Cholistan Desert since 2001 by constructing 70 reservoirs each having a storage capacity 15000 m^3. The other water development interventions include installation of 20 turbine pumps each of 28 liters per second discharge for pumping fresh groundwater and 2 Reverse Osmosis Plants to desalinize the saline groundwater with a capacity of 1000 to 6000 gallons per day. By adopting these water conservation and management techniques, about 1700 million gallons of potable water annually is made available for the human and livestock populations against the requirement of 1681 million gallons. Moreover, these interventions are saving 6000 million rupees per drought in the form of livestock production.

Keywords: Arid area, Pakistan, Cholistan desert, Water conservation.

1. INTRODUCTION

Globally per capita annual water availability will decline from 7800 m^3 in 1990 to 4800 m^3 in 2025 (Shiklomanov and Balonishnikova, 2003). Asia is the most vulnerable continent in the world due to increase in population pressure and aridity. Many arid regions in the continent are even now being turned into desert. Eswaran et al., 1998 reported that desertification has affected about 46% of the world's population.

Pakistan has 70 Mha of arid and semi-arid lands that is about 80% of its total geographical area (PADMU, 1983). Out of this 41 Mha arid area, 11 Mha falls under main deserts where climate is hyper arid (Kahlown and Majeed, 2004). These deserts are: Cholistan (2.6 Mha), Thal (2.3 Mha), Thar (4.3 Mha) and Chagi-Kharan (1.8 Mha) (Figure 1). The Cholistan is a big desert in the Punjab province having the boundary with the Rajistan desert of India in the northeast, and the Thar desert in the west. It is divided into two parts, i.e. greater and smaller. The smaller part comprises flat plains and small sand ridges with undulating to rolling topography, while the greater part consists of big sand dunes with rolling to steep topography. The height of dunes in the greater part varies from 30 to 125 m (Akram and Sheikh, 1999). The desert area consists of sand dunes (1.13 Mha), sandy soil (0.95 Mha), loamy soil (0.06 Mha), and saline-sodic clayey soil (0.44 Mha). The vegetation of the desert is typical of arid tract and consists of xerophytic species (Kahlown and Akram, 2004). The desert is being used as a natural grazing land under an uncontrolled grazing system. Therefore, it causes serious damage to palatable vegetation.

The human population in the Cholistan Desert is about 0.11 million and the livestock population (sheep, goat, cow, camel, donkey) is nearly 2.0 million. The population is scattered at different places depending on the availability of drinking water. Low and sporadic rainfall (166 mm average annual), high temperatures (up to 55^0 C in summer), low humidity, high rate of evaporation and strong summer winds are the main characteristics of the climate. The groundwater is mostly saline and unfit for human and livestock drinking (PCRWR, 2004a). Because of these limiting factors, the local population is nomadic and remains in search of water and fodder for their animals.

The primary source of freshwater in the Cholistan Desert is rainwater, which is collected in natural depressions or man-made ponds locally called tobas. There are more than 1500 tobas in the desert out of which only 500 are in operation (PCRWR, 2004b). These tobas are mostly not in appropriate places because the sites have not been identified based on scientific information, e.g. topographic survey, soil physical and chemical properties, infiltration rate, soil porosity, etc. Most of the rainwater collected in the tobas is lost through seepage and evaporation due to high infiltration rates in sandy soil and temperature with strong winds during summer season. As a result, the stored water lasts only for three to four months. Siltation in tobas is another serious concern, which reduces their storage capacities rapidly, especially during the monsoon season. In order to improve the situation, PCRWR has been actively engaged in various research and development (R&D) activities to uplift the socio-economic conditions of the dwellers.

Figure 1: Main Deserts of Pakistan

2. OBJECTIVES

The objectives were to manage and develop freshwater resources on scientific grounds for drinking by human and livestock populations in the Cholistan Desert, and to uplift the socio-economic status of the desert people.

3. MATERIALS AND METHOD

PCRWR initiated desertification monitoring activities in the Cholistan Desert in 1982 (PCRWR, 1993). During 1988, a field research Station at Dingarh in the Cholistan Desert was established where research activities relating to desertification control were started acquiring 200 hectares of state land. The land of Field Station consists of mobile sand dunes, sandy soils, and dense saline-sodic clayey soils with poor carrying capacity with saline groundwater. In 1989, the first meteorological observatory in the desert was established at the Station to record actual climatic data on rainfall, maximum and minimum temperatures, evaporation, wind speed and relative humidity. The research efforts have been made on water harvesting techniques, saline agriculture, range management, grassland development, sand-dune stabilization and saline agro-forestry in the desert environment. A turbine with discharge of 14 liters per second (lps) having 90 meter depth has been installed to pump groundwater for experimentation under saline irrigation and conjunctive use with collected rainwater. EC, SAR and pH of groundwater are 4.6 dS/m, 14, and 7.5 respectively.

3.1 Experimentation on Rainwater Harvesting

The experiments on rainwater harvesting have been carried out by constructing 7 storage ponds. The depth and storage capacity of the ponds varied from 4 to 6 m and 3200 to 15000 m^3 respectively (Table 1). The side slope of the ponds was 1:2. These ponds were designed to collect maximum rainwater within the shortest possible time and to minimize water losses.

Table 1: Salient Features of Experimental Rainwater Harvesting Ponds

Pond No.	Size (m)			Storage Capacity (m^3)
	Length	Width	Depth	
1	37	37	5	4800
2	46	46	5	6300
3	46	30	4	3200
4	46	30	4	3200
5	46	30	4	3200
6	61	61	6	15000
7	61	61	5	12800

The catchment of the first six ponds was 90 hectares, whereas the catchment for seventh pond was 45 hectares. These catchments consist of flat dense saline-sodic clayey, impervious, very poorly drained soils (Akram and Chandio, 1998). The overall vegetation in the catchment is less than 10% and slope is 0.006% from north towards south. Evaporation losses have been reduced by increasing the depth of ponds as well as by establishing windbreakers around the banks. To reduce seepage losses a polythene sheet (0.127 mm) in the bed of ponds underlain by a layer of 8 cm impervious clay has been provided. However, seepage and evaporation losses are the major concerns in the desert. Monitoring of a newly built traditional storage pond having 3701 m^3 storage capacity showed that about 65% of the water was lost through seepage and evaporation during a period of 8 months where no seepage has been stopped by polythene sheet on the bed under impervious clay (Table 2).

Table 2: Seepage and Evaporation Losses in the Cholistan Desert

Month	Losses (mm)		
	Seepage	Evaporation	Total
September 1989	409	278	687
October 1989	153	205	358
November 1989	120	142	262
December 1989	114	67	181
January 1990	114	95	209
February 1990	113	68	181
March 1990	80	173	253
April 1990	22	254	276
Total	1125	1282	2407

3.2 Development of Water Resources

As a result of field research on rainwater harvesting techniques, PCRWR initiated a 4-year Research and Development (R&D) Programme in 2001 to make water available in the desert for drinking. The water development interventions included collection of rainwater, exploitation of fresh groundwater, and desalinization of saline groundwater to provide sustainable supply of drinking water to the local residents and their livestock. Before constructing 70 storage reservoirs, installing 20 turbines and 2 Reverse Osmosis (RO) units, several activities were undertaken including a reconnaissance survey to identify the suitable catchments and fresh groundwater points, a demographic survey to assess water demands, a topographic survey of the selected catchments to determine the slope for runoff; development of catchments to establish a network of ditches, soil profile investigations of the catchments up to 150 cm and the ponds up to 6 m to determine their physical and chemical properties as well as water holding capacity, hydrological studies to assess the runoff potential of the catchments, design analysis of rainwater harvesting system to estimate the quantity of work for excavation of ponds, and groundwater investigations through resistivity survey and trial bore to identify freshwater aquifers.

4. RESULTS AND DISCUSSIONS

Rainfall is the single source of freshwater in the desert. It has been investigated that there is about 350 million cubic meter (Mm^3) runoff potential available for storage in the desert (Table 3). Results of the research studies conducted at Dingarh Station showed that drinking water requirements of the dwellers could successfully be met through collecting rainwater on scientific grounds. Moreover, the collected water can be utilized in conjunction with saline groundwater for saline agriculture in the desert.

Table 3: Potential Runoff in the Cholistan Desert

Year	**Rainfall (mm)**	**Potential Runoff (mm)**	**Runoff for Storage in Cholistan (Mm^3)**
1989	84.2	38	168
1990	144.1	42	187
1991	173.0	87	385
1992	231.0	115	506
1993	155.9	89	392
1994	299.2	152	672
1995	213.0	131	582
1996	152.0	81	359
1997	201.0	74	327
1998	172.1	65	287
1999	20.8	3	14
2000	126.4	62	273
2001	148.6	50	222
2002	2.0	-	-
2003	240.0	106	467
Average	160.5	79	350

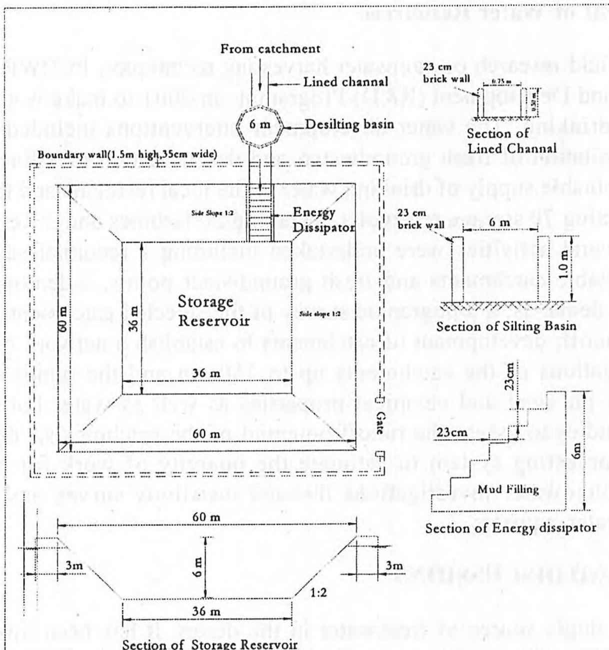

Figure 2: Layout Plan of Rainwater Harvesting System

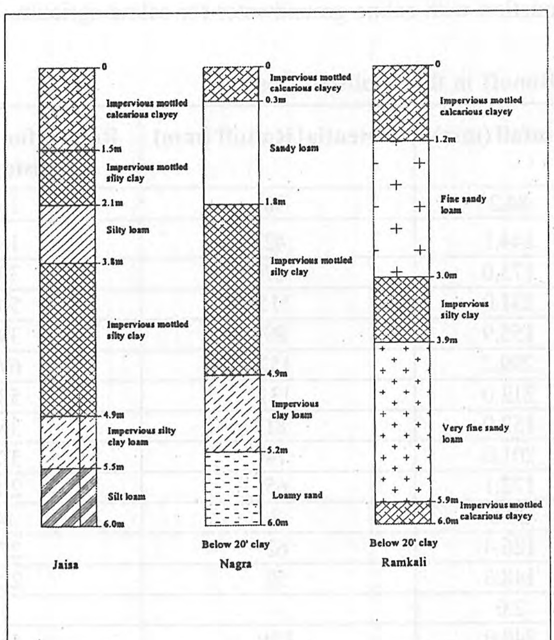

Figure 3: Deep Soil Profile of the Selected Ponds

Table 4: Physical and Chemical Soil Properties of the Selected Catchments

Soil depth (cm)	Texture	Pores	pH	Mottles	Hardness
		Dingarh Fort			
0-9	Clay loam	Common fine vascular	9	Nil	Hard
9-75	Silty clay	A few fine tabular	9	Common fine	Very hard
75-108	Silty clay	——do——	9	——do——	Very hard
108-125	Silty clay	Nil	9	Many fine	Very hard
125-150	Sine sand	Nil	9	Common medium	Friable
		Bariwala Track			
0-8	Clay loam	C. fine vascular	8.8	Nil	Hard
8-35	Silty Clay	Nil	9	C.f.to very fine	Very hard
35-90	Light very fine sand	Nil	9	Many fine	Friable
90-150	Loamy	Nil	9.2	Many fine	Friable

Table 5: Water Quality of Selected Storage Ponds

Month	EC (dS/m)	pH	Turbidity (NTU)
		Nagra	
November 2003	0.56	8.0	828
December 2003	0.56	8.0	803
January 2004	0.57	7.9	683
February 2004	0.59	7.9	638
March 2004	0.65	8.2	616
		Dingarh	
November 2003	0.45	8.0	450
December 2003	0.43	8.0	248
January 2004	0.45	7.7	196
February 2004	0.45	7.9	164
March 2004	0.50	7.5	150
		Nizam Wala	
November 2003	0.23	7.8	86
December 2003	0.24	8.0	76
January 2004	0.27	7.5	69
February 2004	0.27	7.7	56
March 2004	0.31	7.6	46

Table 6: Economic Analysis of a Constructed Reservoir

Description	Quantity
Reservoir capacity (million gallon)	4.00
Capital cost of reservoir (Rs. in million)	1.00
Estimated life of reservoir (years)	50.00
Capital cost per year (Rs. in million)	0.02
Desiltation cost after every five years (Rs. in million)	0.03
Desiltation and maintenance cost per year (Rs. in million)	0.01
Annual cost: capital and maintenance (Rs. in million)	0.03
Cost of collected rainwater per gallon (paisa)	0.75

4.2 Exploitation of Fresh Groundwater

WAPDA explored two fresh groundwater pockets in the Cholistan Desert during the 1980's (PCRWR, 2004). The first aquifer is located near Moajgarh Fort along the abandoned bed of old Hakra River. This pocket covers an area of about 0.14 Mha. The second one is much smaller (0.05 Mha) and is located 90 km northwest of Derawar Fort. However, both the freshwater bodies are underlain and bordered by brackish to saline groundwater. As the exploitation of these freshwater resources needed a very careful planning and designing to avoid saline groundwater intrusion, detailed groundwater investigations were made through a resistivity survey and bore holes before installing 20 turbines. Each turbine has a discharge capacity of 28 lps and depth varies from 55 to 91 m. About 1400 million gallons of drinkable water is available annually for human and livestock population in the desert. Total depth of the turbine varies from 55 to 92 m. The material of the blind pipe was mild steel with 31 and 25 cm diameter with varying depths from 18 to 43 and 7 to 30 m respectively. The brass filter with 25 cm diameter was used having a depth of 22 to 30 m. Economic analysis of turbines are given in Table 7.

Table 7: Economic Analysis of a Turbine

Description	Quantity
Capital cost of turbine (Rs.in million)	1.00
Estimated life of the turbine (years)	10.00
Capital cost per year (Rs. in million)	0.10
Annual fuel consumption (liter)	8640.00
Annual cost of fuel @Rs.21/lit. (Rs. in million)	1.81
Lubrication oil cost @25% of the fuel (Rs. in million)	0.05
Estimated annual repair cost (Rs. in million)	0.03
Annual withdrawal (million gallon)	70.25
Cost per gallon (paisa)	0.50

4.3 Desalinization of Saline Groundwater

Although groundwater is available in the desert, it is mostly moderately saline to highly saline (Akram and Sheikh, 1999). However, this water can be made potable for human consumption through the reverse osmosis technique. An RO unit was installed on an experimental basis in 2003 at the Dingarh Field Station. Salient features of the unit and economic analysis are given in Tables 8 and 9 respectively.

Table 8: Salient Features of Reverse Osmosis Unit

Description	Quantity
Raw water quality (TDS)	4000
Treated water quality (TDS)	200-250
Flow capacity (US gallon/8hrs)	4000
Salt rejection rate (%)	99.2
Product water recovery (%)	60
Type of membrane	FILMTEC BW-30-4040 USA
Number of membranes	8

Size of membrane (cm)	10 x 102
TDS tolerance of membrane (ppm)	>5000
Multi media filter (cm)	41 x 165
Type of filter	Jumbo (51 cm)
Cartridge	RB-I Micron-6 Nos.
UV unit	Are and thumbler tube
Antiscalant/Dosing pump	High impulse 3-5 lit/hr.

Table 9: Economic Analysis of Reverse Osmosis Plant

Description	Quantity
Annual freshwater production (Million gallon)	1.46
Capital cost (Rs. in million)	1.90
Estimated life of plant (Years)	10.00
Annual fuel cost @ Rs.21/liter (Rs. in million)	0.18
Lubrication oil cost of @ 25% of the fuel (Rs. in million)	0.05
Annual repair cost	0.05
Annual chemical cost (Rs. in million)	0.03
Cost of freshwater per gallon (Rs.)	0.34

Table 10: Annual Availability of Freshwater

Source	Water Availability (million gallons)
Rainwater Harvesting	280
Groundwater exploitation	1405
Desalinization	3
Total	**1688**

4.5 Economic and Social Impacts

All these pilot activities have brought about a revolution by creating awareness among the desert people and the concerned development agencies working in the area. This project has saved 6000 million rupees per drought in the form of livestock production due to availability of freshwater for a longer period in the desert. Moreover, about Rs. 200 million per annum would be saved even with average cost of livestock i.e. Rs.10000 per head by reducing migration of the inhabitants. A measure of the success of the programme is that the Cholistan Development Authority is now adopting the PCRWR model for construction of water storage ponds on a large scale. The extrapolation of all these interventions would ultimately help improve the socio-economic conditions of the hyper arid area of the country.

5. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations have been drawn from the efforts made for the development and management of water resources in the Cholistan desert:

i) Out of 350 Mm^3 of runoff potential, 1.05 Mm^3 has been harnessed successfully through scientifically designed 70 pilot earthen ponds in a hyper arid climate. The remaining potential can easily be exploited through adopting the rainwater harvesting strategy developed and tested by PCRWR;
ii) RO technology was found to be useful in the desert. However, local industry should be encouraged to manufacture cheaper RO membranes to reduce the desalinization cost;
iii) About 1700 million gallons of freshwater is economically made available through out the year against the demand of 1681 million gallons. However, maintenance of the system by local people is recommended to make it sustainable;
iv) There is still need to reduce evaporation and seepage losses from the ponds in a desert environment. Therefore, it is recommended that R&D activities should be carried out to evolve the cheapest method for reducing the losses.

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Simulation of Surface Water Runoff and Groundwater Resources in Wadi Ham, UAE

Mohsen Sherif, Ampar Shetty

SIMULATION OF SURFACE WATER RUNOFF AND GROUNDWATER RESOURCES IN WADI HAM, UAE

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ABSTRACT

The availability of water resources in arid and semi arid regions, including the GCC countries, represents the main element of any sustainable development in such areas. Although, drinking water in the GCC countries is mainly produced through desalination of seawater, traditional water resources still constitute the major portion of the total water consumption in the region. Traditional water resources are mainly used for agriculture and industrial purposes. Therefore, every possible effort should be conducted to assess, develop and sustain the traditional water resources in the GCC countries. This paper is devoted to the assessment and simulation of surface water runoff and groundwater resources in Wadi Ham, UAE. It provides a proper methodology for the analysis of rainfall events and assessment of surface water runoff that would develop from the rainfall events. The HEC-HMS model was used to assess the surface water runoff in Wadi Ham under different rainfall events. The model parameters were calibrated to simulate observed surface water storage. The geological and hydrogeological conditions were identified for the aquifer system in the area of Wadi Ham. Groundwater conditions are simulated using MODFLOW. The relation between rainfall and groundwater recharge has been investigated. A comparison between observed and simulated groundwater levels in some observation wells is presented.

Keywords: rainfall, surface water runoff, groundwater, HEC-HMS, MODFLOW.

1. Introduction

The climate in the Arabian Peninsula is marked by long, hot and dry summers, and short, occasionally wet winters. Desert climatic conditions prevail where temperatures may exceed 50°C during June, July and August. Rainfall is scarce and infrequent. The average annual rainfall in the Gulf Cooperation Council (GCC) countries varies between 70 and 140mm. Different topographical features, that reveal the availability of surface water resources, are encountered at Oman Mountains to the east and Asir Mountains to the southwest of Saudi Arabia. The precipitation is higher at these two specific areas, reaching about 500 mm/yr, which causes occasional runoff. The surface water runoff from the western slopes of the Oman Mountains benefits areas in Oman and the United Arab Emirates (UAE). The GCC countries experience an evident shortage in the renewable water resources and hence have emphasized on the non-traditional water resources with specific reference to the desalinated water.

The average annual volume of rainwater in the GCC is estimated at 205.93 billion m^3. The total surface runoff generated from rainfall is estimated to be 4.83 billion m^3/yr [1]. Several dams have been constructed across the main Wadis in arid regions to harvest the surface water runoff and enhance the groundwater recharge and develop the groundwater resources. Groundwater resources in the GCC countries can be classified into partly renewable resources, which are mostly encountered in shallow alluvial aquifers, and non-renewable resources (or fossil water) which are encountered in the deep aquifers. The potentiality of the shallow aquifers is relatively small. It depends on the rainfall events and surface runoff, and thus may vary considerably from one year to the other. Groundwater resources represent the major water supply for agriculture demands in the GCC countries.

This paper presents a methodology for the assessment of surface water and groundwater resources in Wadi Ham, Fujairah, UAE. Rainfall characteristics were identified using available data. The HEC-HMS model was used to assess the surface water runoff in Wadi Ham under different rainfall events. The model parameters were calibrated to simulate observed surface water storage. MODFLOW was calibrated and validated over a total duration of 15 years. The observed and simulated hydrographs in the different observation wells were in good agreement.

2. Physical Setting of UAE and Wadi Ham

The UAE lies in the southeastern part of the Arabian peninsula between latitudes 22° 40' and 26° 00' North and longitudes 51° 00' and 56° 00' East. It is bounded from the north by the Arabian Gulf, on the east by the Sultanate of Oman, the Gulf of Oman and on the south and on the west by the Kingdom of Saudi Arabia, Fig. 1. The area of the UAE is 83,600 km^2. Its land is mostly desert and is characterized by the predominance of Aeolian Landform System. The geomorphologic features include mountains, gravel plains, sand dunes, coastal zones and drainage basins [2].

The Wadi Ham rises in the mountains immediately south and south east of the Masafi draining south eastwards into the Gulf of Oman between Fujairah and Kalba. It is deeply incised in its upper portion and is characterized by narrow valleys and steep slopes leading down to the wadi floor of coarse alluvial gravels and boulders. The gradient of the flood plain is very low and it forms a broad flat area between the dam and the sea.

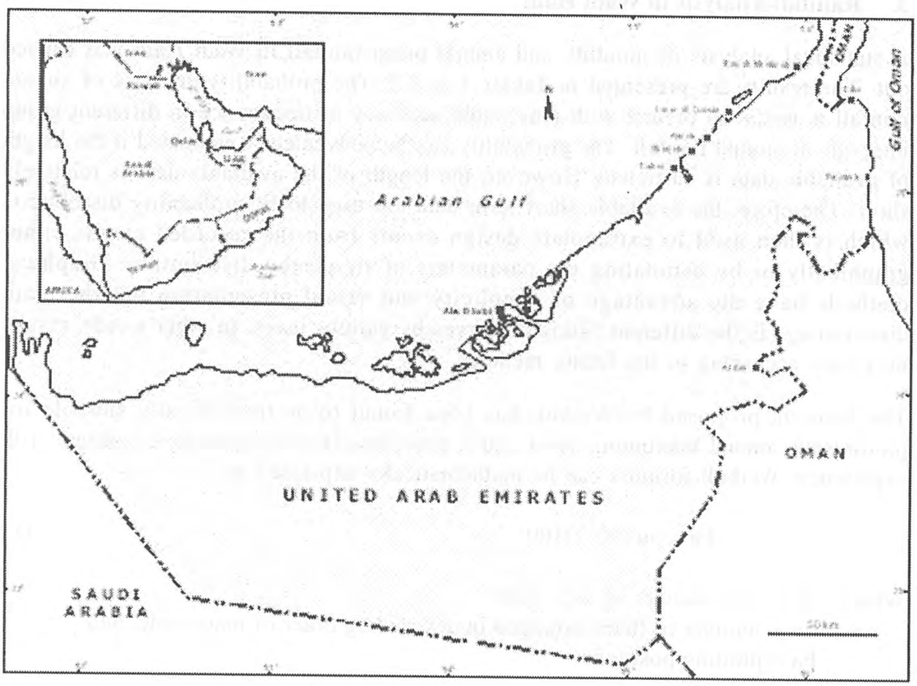

Fig. 1: Physical setting of the United Arab Emirates.

Wadi Ham valley floor is a flat-gravelly plain with a triangular shape broadening to the sea and draining the surrounding mountains. It rises from sea level at Fujairah to approximately 100m above sea level; to the northwest. A few hills are scattered in different parts of the wadi and subdivide it into communicative zones. Along the coast it is a coastal plain, land inward it becomes a river terrace or alluvial plain. It is locally dissected by stream channels filled with cobble and gravel [3]. The number and the depth of channels decrease towards the coast. Towards the coast the wadi/coastal plain is used for extensive agricultural activities and new industries. A remote sensing image for the area of Wadi Ham is presented in Fig. 2.

3. Rainfall Analysis in Wadi Ham

A statistical analysis of monthly and annual mean rainfall in Wadi Ham was carried out. The results are presented in Tables 1 and 2. The probability analysis of annual rainfall is useful to predict with reasonable accuracy of occurrence in different group intervals of annual rainfall. The probability can be conveniently estimated if the length of available data is sufficient. However, the length of the available data is relatively short. Therefore, the available short term data are used to fit probability distribution which is then used to extrapolate design events from the recorded events either graphically or by estimating the parameters of frequency distribution. Graphical methods have the advantage of simplicity and visual presentation but the main disadvantage is the different fitting of curves by various users. In other words, results may vary according to the fitting methods.

The formula proposed by Weibull has been found to be theoretically suitable for plotting the annual maximum series and it provides estimates that are consistent with experience. Weibull formula can be mathematically expressed as:

$$Fa = (m / N+1)100 \tag{1}$$

Where: N = total number of data items
m = number of items arranged in descending order of magnitude, and
Fa = plotting position.

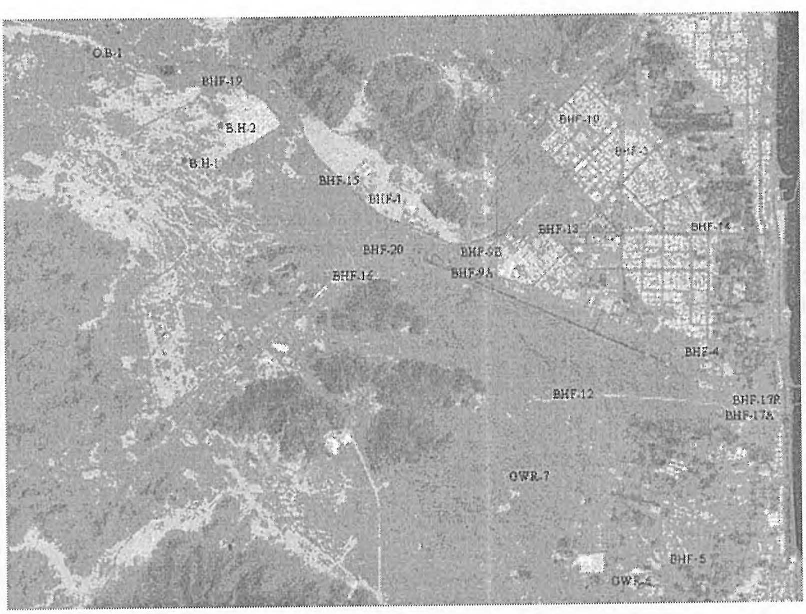

Fig. 2: An image for the downstream area of Wadi Ham.

Table 1: Statistical value of monthly rainfall distribution in Wadi Ham.

Month	Rainfall Range (mm)	Mean (mm)	% of Normal R-Fall	S.D. (mm)
October	0-35	4	2	8
November	0-31	5	3	9
December	0-179	17	12	40
January	0-106	18	12	25
February	0-184	41	27	61
March	0-145	40	27	54
April	0-50	11	7	17
May	0-30	3	2	8
June	0-11	2	1	3
July	0-75	6	4	16
August	0-27	2	2	6
September	0-10	2	1	3

Table 2: Statistical value of annual and one-day maximum rainfall distribution.

Statistical parameter	Annual rainfall distribution	One-day annual maximum rainfall distribution
Rainfall range (mm)	4-506	2-137
Mean (mm)	151	50
Standard Deviation (mm)	127	34
Kurtosis	1.36	0.69
Coefficient of Asymmetry	1.18	1.06
Prob. of occurrence of 75% normal	51	57
Prob. of occurrence of 50% normal	64	79

The one day annual maximum and the mean annual rainfall data for Wadi Ham have been analyzed for estimating the expected rainfall at different return periods using Gauss, Lognormal, Gumble, Pearson Type -III and Weibull formula. Weibull was found to give better consistency in estimating the return periods when compared with other distributions in the present study. Therefore, Weibull formula was used to estimate the return periods and the 95% confidence interval was drawn to indicate the likely range of the true value of the quantile. Rainfall for different probabilities for one day annual maximum and annual mean rainfall were determined from probability graphs and corresponding values were worked out. Plots are presented in Figs. 3 and 4.

Rainfall is distributed from January to December with the maximum occurring during the months of February and March and also about 50% of the annual rainfall normally occurs during these two months. Monthly rainfall values range from 0 to 184mm, mean monthly rainfall varies from 1.6mm to 40.6mm with variation of the standard deviation from 2.7mm to 60.9mm. The monthly standard deviation exceeds the monthly average precipitation. This reveals that the year-to-year monthly variation in precipitation is quite high in the area.

4. The HEC-HMS Model

The Hydrologic Modeling System, HMS [4] is designed to simulate precipitation-runoff processes of dendritic watershed systems. In addition to unit hydrographs and hydrologic routing options, the model capabilities include a quasi-distributed runoff transformation that can be applied with girded (e.g., radar) rainfall data, and a simple "moisture depletion" option that can be used for continuous simulation. The execution of the program requires specification of three sets of data. The first, labeled Basin Model, contains parameters and connectivity data for hydrologic elements. The possible types of elements include sub-basin, routing reach, junction, reservoir, source, sink, and diversion. The second set, Precipitation Model, consists of meteorological data and other related information required to process it. The model may represent historical or hypothetical conditions. The third set, Control Specifications, specifies time-related information for a simulation.

The model of Wadi Ham contains only 4 of 7 elements in the basin model. There are 10 hydrologic elements in the Wadi Ham model, made up of 4 subbasins, 3 river reaches, 2 junctions, and 1 sink is considered at the Wadi Ham reservoir, Fig. 5. The meteorological model contains precipitation data, either historical or hypothetical for the HEC-HMS model. The number of rain gauges and its Thiessen weights considered for the subbasins are presented in Table 3. The control specifications contain all information related to the time of events for the model, including the start time and date, stop time and date, and computational time step of the simulation. Control specifications were separately selected for all the events of rainfall considered for the simulation. Raw geometric data such as length, slope, area, centroid location, and information such as soil types and landuse/land cover description which are used to characterize the abstractions are manually processed and presented in Table 4. However, other parameters like the basin coefficient (Ct), Unit Hydrograph peaking coefficient (Cp) were selected based on a previous study [5] in which Ct typically ranges from 1.8 to 2.2 although it has been found to vary from 0.4 in mountainous areas to 8.0 along the Gulf of Mexico. It is also reported that Cp ranges from 0.4 to 0.8, where larger values of Cp are associated with smaller values of Ct.

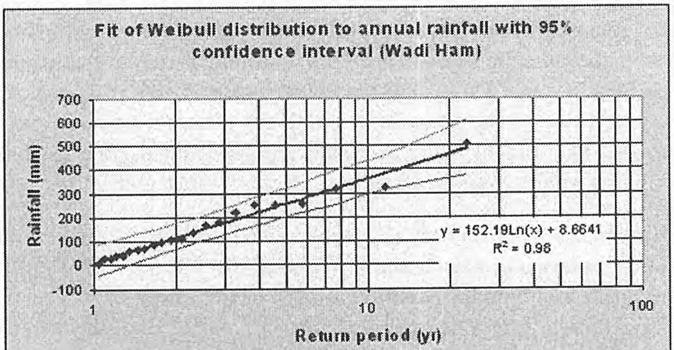

Fig. 3: Probability graph for the annual rainfall, 95% confidence interval.

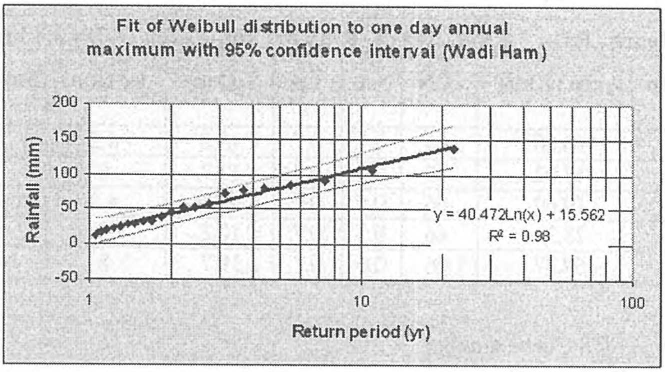

Fig. 4: Probability graph for the one-day annual maximum rainfall, 95% confidence interval.

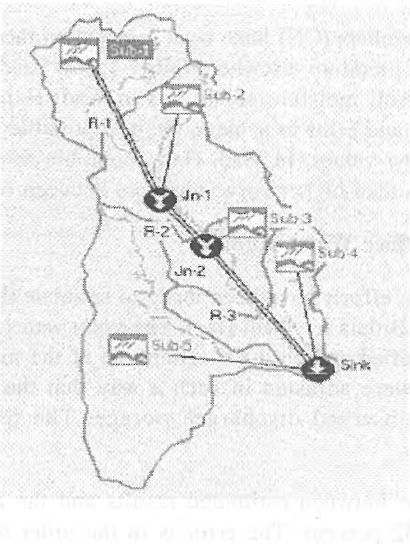

Fig. 5: Schematic basin model of Wadi Ham.

Table 3: Rain gauges and weights considered for each sub-basin in Wadi Ham.

Sub-basin	Area (Km^2)	Rain gauge	Thiessen Weight	Rain gauge Weight	Thiessen
1	30.80	Masfi	1.00	-	-
2	47.02	Masfi	0.40	Bithna	0.60
3	19.69	Bithna	1.00	-	-
4	28.34	Bithna	0.70	Farah	0.30
5	69.37	Bithna	0.35	Farah	0.65

Table 4: Basin model parameters of Wadi Ham.

Reach (R1)= 7.8 km, Reach (R2)= 6.0 km, Reach (R3)= 4.4 km							
Sub-basin	**Area (Km^2)**	**CN**	**Ct**	**Cp**	**L (km)**	**Lc (km)**	**Snyder lag (hr)**
1	30.80	69	0.5	0.7	13.2	4.5	1.28
2	47.02	69	0.5	0.7	12.7	6	1.38
3	19.69	66	0.5	0.7	8.2	4.5	1.11
4	28.34	66	0.5	0.7	10.2	5	1.22
5	69.37	66	0.6	0.7	19.7	8	2.05

Where:

CN = SCS Curve number

C_t = Basin coefficient

C_p = UH peaking coefficient

L = Length of the main stream from the outlet to the divide

L_c = Length along the main stream from the outlet to the nearest point to the centroid of the watershed.

The initial SCS curve numbers (CN) have been selected on the basis of experience and the values quoted in the literature elsewhere (NEH-4; [6]) based on the hydrologic soil groups and antecedent soil moisture conditions in Wadi Ham. However, CN values were readjusted by trial and error to achieve the best possible results comparable with the observed storage/flow values. In Wadi Ham, ophiolite formation with steep basin relief was considered to take higher curve numbers between 66 and 69.

5. Assessment of Surface Water Runoff

As an initial application, efforts have been made to simulate the discharge/yield at the flood gauging station at Bithna for Wadi Ham. The event water yield and corresponding storm events were identified and used for calibration of the model. By trial and error, the model parameters were adjusted in such a way that the estimated discharge is comparable with the observed discharge/ storage. The results are presented in Table 5.

The percentage of error between estimated results and the actual measurements is ranging between 1 to 32 percent. The error is in the order of 5% for the relatively "important" big storms with water storage of more than 2.0 MCM. The above results indicate that the difference of simulated and observed storage/yields is within the allowable limit except for few cases of small water storage. The difference may be attributed to the error in some of the input values such as precipitation and its distribution, storage/yield information and initial abstraction coefficients (0.2) and SCS curve numbers which may be varied on soil moisture conditions. However, parameters like Ct and Cp are insignificant in terms of total yield of the catchment.

Table 5: Estimated and observed flow at Bithna gauging station (Wadi Ham).

Storm Date	Rainfall depth (mm)			Duration (hr)	Intensity (mm/hr)	Estimated flow (mcm)	Observed flow (mcm)
	Masafi	Bithna	Farfar				
13.2.82	120	158	148	34	3.9	5.2233	5.388123
10.2.83	29	144	115	48	1.6	1.608	1.591329
30.3.83	50	72	85	34	2.0	1.1884	1.747948
16.2.88	146	216	162	42	3.7	6.6773	6.935626
11.12.95	64	83	86	38	2.0	1.530	1.18562
24.1.96	54	100	85	34	2.1	1.273	0.98645

6. Groundwater Recharge and Simulation

The study domain for Wadi Ham aquifer comprises an area of 117.81 km^2 with total length of 11.9 km east to west (from the dam to the coast of Oman Gulf) and 9.9km from north to south (Fujairah to Khalba) as shown in the Fig. 6. The modeled area and the aquifer boundaries were delineated by digitizing the remote sensing image of Wadi Ham. At the coast, many cells are located in the sea which is considered to be constant head cells of head 0.0 m (sea level). Ponding area was delineated and marked on the study domain. The total area of ponding at flood level is about 0.40 km^2.

The study area was divided into 119 columns and 99 rows. The size of the cell is 100 m by 100 m. The model is comprised of a total of 11781 equally spaced cells. However, net area of aquifer consisting of only about 64.94 km^2 with 6494 active cells. The area of inactive cells is about 50.7 km^2 that makes 5287 cells.

A stress period is defined as a time period during which all time dependent processes such as pumping and recharge are constant. The calibration period was taken from January 1989 to December 1993. The validation period was taken from January 1994 to December 2004. For the modeling purpose, the storage depth has been distributed in space to the 40 cells within the area of storage (0.40 km^2) of the dam and in time to the total period of storage as m/day. The average period of storage for each event in the dam is considered approximately 60 days.

Groundwater is exploited intensively from the sand and gravel aquifer for irrigation in the coastal plain between Fujairah and Khawr Kalbha. Several well fields are in operation for the domestic water supply by the Ministry of Electricity and Water including:

1. Fujairah well field with 3.2 million m^3/year until 1988, very limited groundwater extraction since 1988.

2. Shaara well field, 2 km downstream of Wadi Ham in the wadi section of the aquifer pumping 1 million m^3/year since 1988 and pumping duration was about 10 hr per day. However, out of 9 wells 5 wells have dried up in the year 2003. Discharges of the wells were drastically reduced from 1988 to 2003.

3. New well field with about 60 wells is operated since 1995 near Kalbha. The total draft is about 6million m^3/year. However, a number of wells were in operation before 1995.

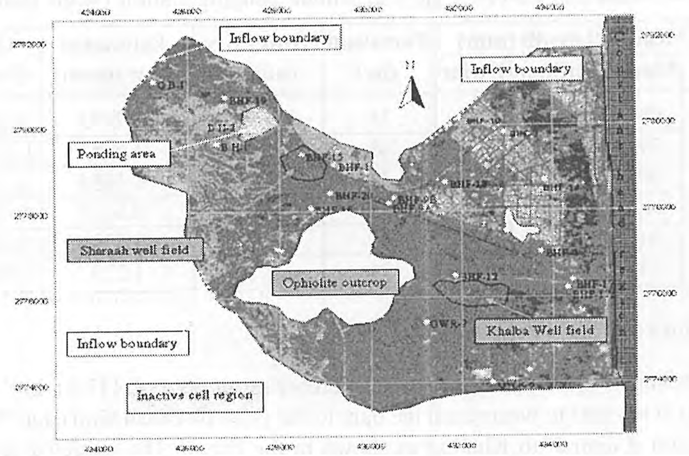

Figure 6: Study domain and boundary conditions in Wadi Ham.

7. Calibration of MODFLOW

The calibration was done for 5 yrs from January 1989 to December 1993 (1826 days). The length of the stress period in this exercise was taken as one month. However, the period during which recharge either due to rainfall or dam storage duly considered as an extra stress period. The total number of stress intervals considered for the calibration period was 146.

The finite-difference technique employed by the MODFLOW requires each stress period to be discretized into several time steps to obtain an accurate solution. The smaller the time steps, the more accurate the solution obtained. The time step multiplier is a factor that can be used to increment the time step size within each stress period. A time step multiplier value greater than one will produce smaller time steps at the beginning of a stress period resulting in better representation of the changes of the transient flow field. Thus, increase in the number of time steps in a simulation may result in smoother head or drawdown versus time curves. Therefore, 10 time steps in each stress period with a time step multiplier of 1.2 were considered in the calibration period.

The model calibration was achieved by changing three parameters, namely, permeability, specific yield and pumping rates. Abstraction and inflow across the boundaries were also simulated by a number of computer runs till the desirable calculated head in all observation wells was achieved.

The recharge due to rainfall was also adjusted to ensure that the calculated heads at observation points are reasonably matching the field measurements. The recharge factor is around 20 percent of the rainfall. Although relatively high, the sand and gravel nature of the aquifer system in the study area allows for such recharge. On the other hand, field observations indicated the direct effect of rainfall events on groundwater levels. The recharge factor in the ponding area was considered in the order of 40 percent.

Time series graphs of simulated versus observed groundwater levels are shown in Fig. 7 for two observation wells. The model simulates very closely the trends and groundwater levels resulting from the groundwater abstractions and recharge from the reservoir storage and rainfall events. However, the limited discrepancies may be attributed to the accuracy of observed groundwater levels as measurements are taken once every month and not necessary on the same day.

8. Validation of the Model

The validation was carried out for duration of 10 years from January 1994 to December 2004. The stress period was also taken as one month. The total number of stress periods considered for the validation period was 244. The same number of time steps and the same time step multiplier as in calibration were considered in the validation period to obtain more accurate and smoother head or drawdown (hydrographs).

The history of storage from 1994 to 2004 is presented in Table 5. The pumping rate at Saraah well field during the initial period of validation was about 3150 m^3/day. This rate was gradually decreased down to reach 1700 m^3/day. This represents the closing down of a few wells in the Saraah well field either due to drying up of wells or the deterioration of the water quality. However, during the maximum pumping rate, the total volume of abstraction from the well field was 1.150 MCM which is about the same pumping during the year 1988.

In Fujairah well field, the draft rate scaled down from 2250 m^3/day to 750 m^3/day during the validation period. Pumping from several wells in this field was terminated during the period under consideration.

The well field at Kalbha experienced a significant increase in pumping rate from 4000 m^3/day to 20000 m^3/day. The number of wells has increased significantly after 1995. The present pumping rate is considered as 20000 m^3/day, which is more or less the same pumping rate that was provided by the Sharjah Electricity and Water Authority.

Table 5: Depth of reservoir storage and recharge depth.

Year	Month	Date	Storage in volume MCM)	Storage in depth (m/day)	Recharge depth (m)
1993	Dec	25	1.52	3.760961	0.025073
1995	Mar	14&22	0.5	1.237158	0.008248
1995	Dec	7	0.55	1.360874	0.009072
1997	Mar	26	1.4	3.464043	0.023094
1997	Apr	22	1.2	2.96918	0.019795
1997	Oct	31	0.505	1.24953	0.00833
1998	Feb	22	0.5	1.237158	0.008248
1998	Mar	3	0.12	0.296918	0.001979

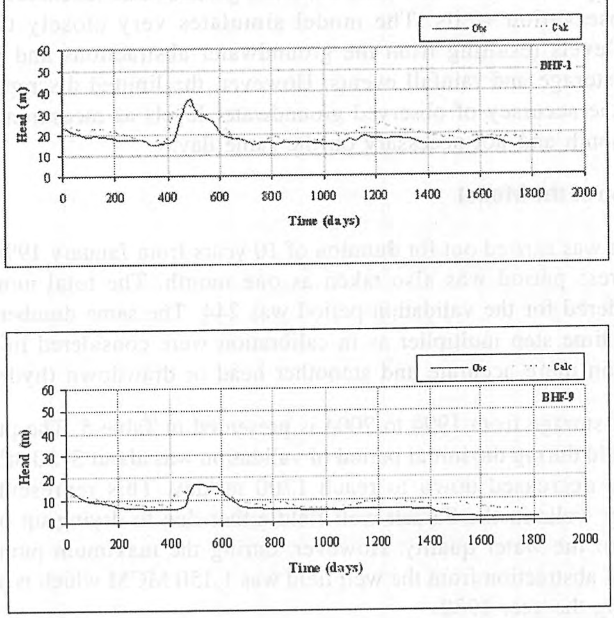

Figure 7: Observed and simulated hydrographs of wells BHF-1 and BHF-9, calibration period.

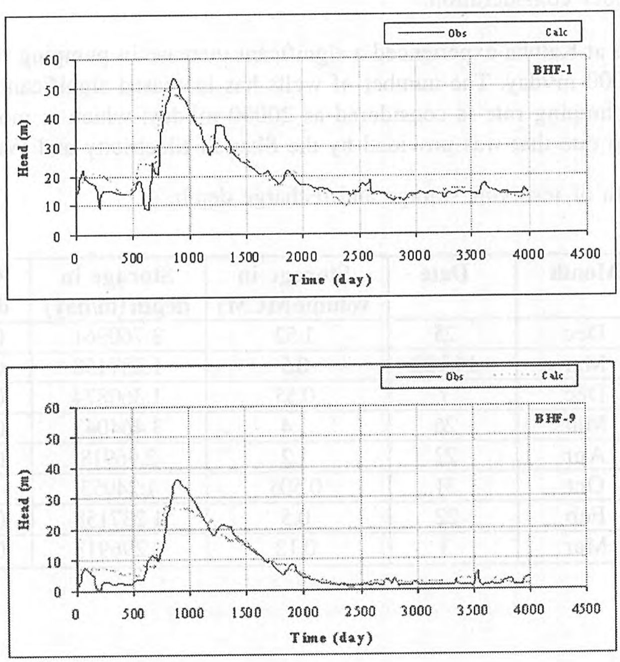

Figure 8: Observed and simulated hydrographs of wells BHF-1 and BHF-9, validation period.

A good match between the observed and simulated hydrographs was obtained. Fig. 8 presents a comparison between observed and simulated hydrographs for observation wells BHF-1 and BHF-9. In some observation wells the observed and simulated values of low and peak heads showed some discrepancy. This may be attributed to the fact that the exact day of recording the groundwater levels in the monitoring wells is not known and is not fixed from one month to the other. Observation wells which are close to the dam are more sensitive than the wells located away from the dam.

1. Conclusions

The characteristics of rainfall events in Wadi Ham, UAE were identified based on the available records. Statistical methods were used to determine the annual rainfall and maximum one-day distribution and their probability of occurrence. The return periods for maximum annual and maximum one day rainfall were also identified. The HEC-HMS model was used to estimate the surface water runoff and storage under different rainfall events. The parameters were calibrated and the estimated water storage was compared with the observed storage in the dam. MODFLOW was used to simulate the groundwater conditions in the aquifer of Wadi Ham. The model parameters were calibrated for a duration of 5 years. The validation period extended for another 10 years. A good match was observed between observed and simulated water levels in observation wells.

Acknowledgement

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GIS-based hydrogeological studies for the assessment of groundwater recharge from the dam of Wai Al Bih, UAE

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Hassan Garamoon and Nada Al Swaidi

GIS-BASED HYDROGEOLOGICAL STUDIES FOR THE ASSESSMENT OF GROUNDWATERRECHARGE FROM THE DAM OF WADI AL BIH, UAE

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ABSTRACT

Wadi Al Bih is considered as one of the major wadies in Ras Al Khaimah Emirate, UAE. Its drainage basin has a moderate to high flash flood hazard which occurs approximately every three to four years. To reduce the flash flood hazard, an earth fill dam was constructed in 1982 in Wadi Al Bih. The present hydrogeological studies are conducted to determine the impact of this dam on the groundwater recharge. Following time and spatial queries, the hydrogeological data were stored in a GIS-database which can be easily used for groundwater numerical modeling and developing a sustainable groundwater resource management scheme. The obtained results indicated that the lithological characteristics and tectonic setting is strongly affecting the groundwater flow pattern as well as the potentiality of the aquifers.

Keywords: Wadi Al Bih hydrogeology, artificial groundwater aquifers recharge, GIS Applications in hydrogeology

1. Introduction

Wadi Al Bih is one of the largest wadis in the northern Emirates of UAE. It consists of an extensive network of valleys comprising a surface area of 483 Km2.extending between Latitudes 25° 40′ and 26° 00′ and Longitudes 56° 00′ and 56° 20′ (only the studied area is shown in Fig. 1). The maximum elevation is 2087 m above mean sea level (amsl). The minimum elevation near the outlet at Burayrat is 65 m (amsl). The catachment is underlain by limestone and characterized by a rugged topography with steep slopes (average gradient is 1:250) and no vegetation. Average annual rainfall is 110 mm (MAF, 2001). The amount of rain that can fall in a single storm can exceed the total rainfall of a dry year (35.8 mm were measured for year 1984). On April 17th, 2003 about 85 mm was recorded at the same station. The estimated annual recharge for groundwater aquifers in Wadi Al Bih is approximately 9.57 Mm3 (MGGS, 1996; Al Assam, 1997). Before the construction of a desalination plant in 1998, groundwater abstracted from these aquifers was the only source of fresh water for domestic use in Ras Al Khaimah city.

The drainage net of Wadi Al Bih basin is external, well developed, and mostly controlled by geologic structures. The hydrologic assessment shows that the Wadi Al Bih drainage basin is considered as moderate but the degree of flash flood hazard tends to be high. High floods are repeated every three to four years.

Evolved from its prime role to develop the water resources in the country, the Ministry of Agriculture and Fisheries (MAF) has constructed a large number of detention and retention dams across the main Wadis. Detention dams are designed to retard the flow velocities and allow appropriate time for the recharge process. Retention dams are designed for water storage with large quantities and relatively high hydraulic heads. Wadi Al Bih main and secondary dams were constructed in the outlet area of Wadi Al Bih (near Bih-1 well, Fig. 1), Ras Al Khaimah to reduce the flash flood hazard and consequently increased groundwater recharge around the dam area. The fluctuations of the water table levels are monitored by six groundwater observation wells constructed up and down-stream of the dams (Fig. 1).

The main objective of this article is to discuss the geological and hydrogeological setting of Wadi Al Bih area and determine the efficiency of the constructed dams in enhancing the recharge of shallow aquifers.

2. Geological and Hydrogeological Setting

Permian to Early Triassic dolomites and dolomitized limestones are characteristic for the Russ al Jibal group (Fig. 2). The sediments were deposited in shallow water on the continental margin of Arabia. It is subdivided into:

- Bih Formation
- Hagil Formation
- Ghail Formation

Bih Formation is Permian in age and has a thickness ranging between 200 and 650 meters (Geoconsult and Bin Ham, 1985). It consists of light to dark grey colored well bedded dolomite which has numerous joints and fissures.

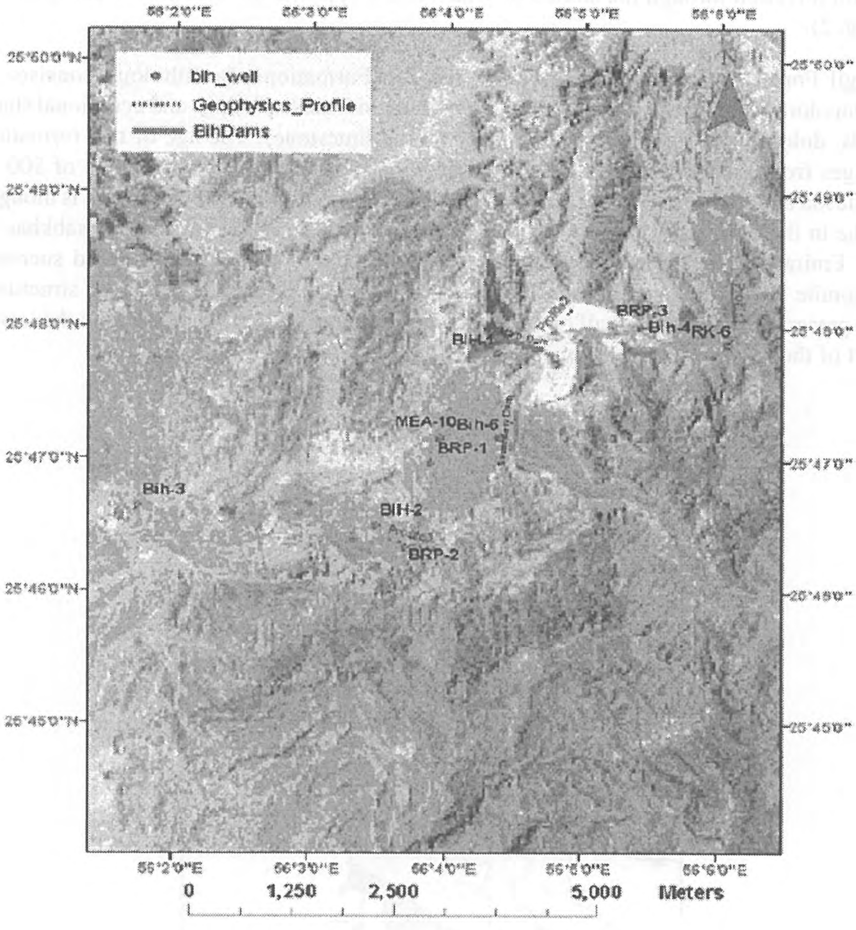


Figure1: A recent satellite image of the studied area in Wadi Al Bih with the locations of monitoring wells, a production well and geophysical profiles.

Electrowatt (1981) reported that the dolomite in the vicinity of the main dam shows bedding with a strike of 20 dips 45 to the east. It also identified two distinct joints with strikes of 325 and 20 and dips of 80 north and 60 west respectively. Structurally the eastward dipping dolomite in the vicinity of the main dams forms part of the eastern limb of an anticline which plunges to the south. There is a major fault running through the dolomite in a north-south direction through the stretch of Wadi Al Bih opposite the mouth of Wadi Qada'ah (Fig. 2).

Hagil Formation conformably overlies the Bih Formations. Its lithology consists of lightcolored, fine grained argillaceous limestones with shale partings and occasional shale beds, dolomitized limestone, and slightly oolitic limestones. The age of this formation ranges from Late Permian to Early Triassic. Ghail Formation has a thickness of 500 m (Hudson and Chatton, 1959). The age is Triassic. The environment of deposition is thought to be in the tidal zone, conforming to dolomite deposition in the present day sabkhas in the Emirates. The formation consists of a thick massive-bedded buff-colored sucrosic dolomite interbeded with dolomitized limestone. Relic pelletal and bioclastic structures are preserved in the upper half of the formation and large scale cross-bedding in the lower part of the formation.

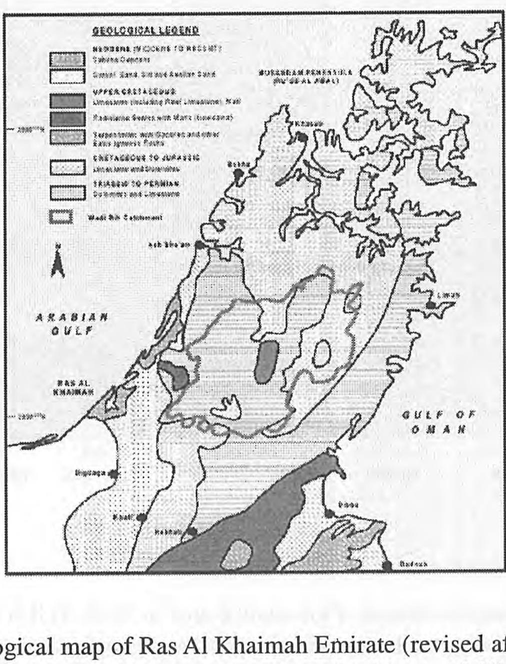


Figure 2: Geological map of Ras Al Khaimah Emirate (revised after Sir Williams Halcrow & Partners Consulting Engineers, 1969).

The drilling information of the old and newly drilled monitoring wells was used to draw a subsurface geologic cross section (Fig. 3). The alluvial cover has an average thickness of 80 meters and consists mainly of two units. The upper unit is loose superficial wadi gravels and based on the age of deposition they are subdivided into recent, young and old. The recent deposition comprised of cobbles and boulders with some sandy gravel and silt with a thickness varying from 3 to 48 m. However, old wadi gravel with mostly silt, cobbles and boulders and some sandy gravels with a thickness ranging from 6 to to 110 meters. The lower unit is composed of debris from gravel to boulder size and is partly cemented by calcite and silica. The depth of this layer base is ranging from 80 to 160 meters below ground level over Wadi Al Bih area (Fig. 3). It is considered as a transition zone between the base sequence of the alluvial gravels, and the weathered top surface of the limestone basements. This layer overlies Hagil Formation.

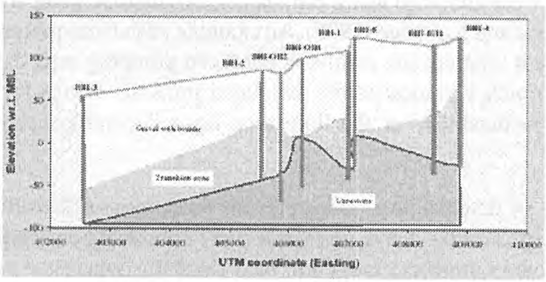


Figure 3: Subsurface geological cross-section along the SW-NE direction. See Figure 1 for wells location.

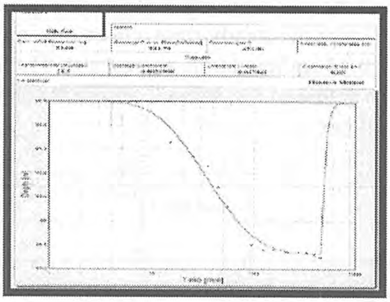


Figure 4: Interpretation of pumping test experiment data conducted for well Bih-5 and an observation well 23 meters apart using GWW program.

Table 1: Estimated aquifer parameters.

Borehole	UTM coordinate		T (MGGS 1996)	T Hantush's (1956) method	Storativity
	Northing	Easting	m^2/d	m^2/d	
BIH-OB1	2852009	406232		0.532	
BIH-OB2	2850828	405893		20-195	
BIH-5	2852261	407089	47	6-25	$4.9 \times 10^{-2} - 2.2 \times 10^{-3}$

Karst feature in Bih formations were deduced from the presence of levels with rounded fragments, coinciding with water volume increase at these levels as well as the identification of fractures zones on the caliper logs of some wells (e.g. Well-RK-6). Lithological logs of MAF boreholes (1-6) and the newly drilled wells BRP-1 and BRP-2 indicated that groundwater resides within the carbonate sequence with the overlying alluvial gravels being dry at the upstream side of the dam. Thus, the upper part of Bih Formation together with the overlying Hagil Formation is considered as the major groundwater aquifer in the area and its potentiality is completely depending on the degree of karstification.

A continuous pumping test was carried out on well Bih-5 in 1996. The rate of pumping was 235 m3/day and the observation data were taken from the pumping well and an observation well at a distance of 23 meters from it. Two more pumping tests were conducted on well number BRP-1 and BRP-2 in the month of December 2003 for 150 and 720 minutes respectively. The shallow aquifer is considered to be semi-confined and thus the drawdown curves were analyzed using Hantush (1956) method using a computer program written by Braticevic and Karanjac (1995). An example of the interpreted drawdown curves is shown in Figure 4 whereas the results of analyzed pumping tests data are listed in the Table 1. The too much variation in the estimated transmissivities for these three wells confirm that the permeability of the limestone layer depend entirely on its degree of karstification.

With an objective of determining some relevant properties of the alluvial sediments at Wadi Al Bih, two infiltration-test experiments were conducted on Wadi Al Bih. The sites of tests were selected within the lakes and near the dams where the recharge process is expected to encounter. Soil samples were also collected for mechanical analysis and assessment of soilmoisture contents. The soil samples were collected up to 40 cm below the ground surface. Measurement of infiltration rate (Ir) is simply achieved by pounding water in a closed container and measuring the rate of head loss using the double-ring infiltrometer. An example of the measured infiltration curves for the sediments of Wadi Al Bih is shown in Figure 5. Under the steady state conditions, the infiltration rate was 0.17 cm/min in the first site and 0.41 cm/min in the second site. These values cover silty gravel range and reflect the coarse nature of the alluvial sediments of Wadi Al Bih, especially in the lower portion of the soil bed.

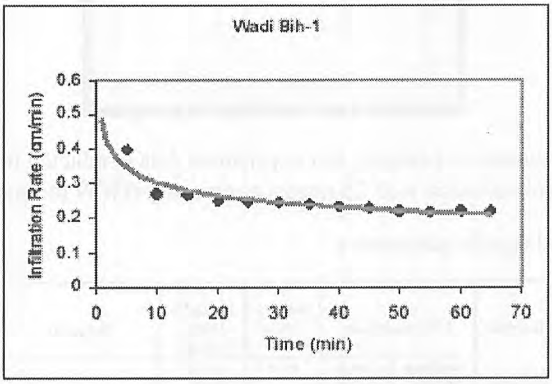


Figure 5: Infiltration rate curve at site one, Wadi Al Bih. 7

3. Analysis of Groundwater Levels

The change in storage of groundwater in an aquifer is reflected by the change in groundwater levels. Usually the change in groundwater storage is a seasonal phenomenon. Significant variations are recognized in the groundwater levels based on whether measurements are taken in the summer or winter seasons. For comparison purposes, the time (month) of measurements should be kept the same.

In order to assess the effect of rainfall events and identify the effectiveness of the constructed dams, monthly groundwater level data for six observation wells in the Wadi Al Bih area have been selected for the groundwater table analysis. There is a significant variation in the groundwater level in response to recharge events with the fluctuation of water table up to 19 m. The maximum groundwater levels were observed in the year 1998. The maximum water table fluctuation was found in well BIH-1 which is very close to the dam site. The minimum water table variation was observed at the well BIH-3 (Fig. 6). The groundwater gradient in the plain area is lower when compared with the gradient of groundwater within the wadi valley close to the dam area.

The monthly rainfall is also plotted on the same figure to identify the relationship between rainfall and groundwater levels. A clear correlation between the rainfall and groundwater is observed for all wells. Successive rainfall storms have more impacts on the groundwater level.

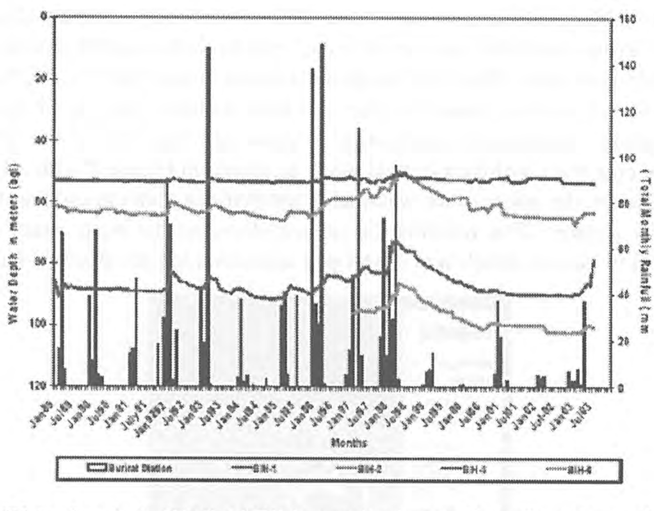


Figure 6: Water levels in Wadi Al Bih's monitoring wells and total monthly rainfall recorded in the nearby Burairat climatological station in the period 1989-2003.

4. Application of GIS for the Database Formulization

Data were collected from existing data bases and maps and through recent field measurements. Hydrogeological, geophysical and remote-sensing techniques are commonly used to assess parameters related to soil, the unsaturated zone, geomorphology, and climate. All these environmental data need to be managed and this can be achieved using databases, particularly GIS databases (Gossel et al., 2004; Gogu et al., 2004).

GIS databases have the following advantages: (1) it is the only system for input, storage, manipulation, and output of geographically referenced data, (2) GIS provides a means of representing the real world through integrated layers of constituent spatial information (Corwin 1996); and (3) Geographic information can be represented in GIS as object or field. The object approach represents the real world through simple objects such as points, lines, and areas. The objects, representing entities, are characterized by geometry, topology, and non-spatial attribute values (Heuvelink, 1998 and Gogu et al., 2004).

In hydrogeology, some examples of spatial objects are wells, piezometers, boreholes, galleries, and zone of protections. Attribute values of objects could be the number of a well, its total depth, location, ownership,etc. The field approach represents the real world as fields of attribute data without defining objects; some example are strata elevation, hydraulic head, total dissolved solids, ...etc. The fields are often associated with vector and raster data models. The vector model represents spatial phenomena through differences in the distribution of properties of points, lines, and areas (Gogu et al., 2004). Storing and manipulating environmental data through spatial relationships can be achieved with GIS packages using the "georelational" model or the "geodatabase" model (Gogu et al., 2004).

Information specific to geomorphologic, geologic, and hydrologic conditions of Wadi Al Bih were divided into primary and secondary data. The primary data section contains layers of general environmental information, such as topography, geological maps, satellite image, and raw hydrogeological data such well lithology, piezometers, dams, etc. Secondary data consists of data derived from processed primary data; examples include hydraulic head and conductivity maps, and also the interpreted geophysical data.

The available drilling information up to year 2004 of the fully and partially penetrating wells as well as the available geological cross sections were digitized and entered into formulated GIS data base. The USGS digital elevation model (DEM) of UAE (Figure 7) was used to determine the ground surface elevation which is the top of the first model layer. The digitized lithological and hydrogeological information together with the DEM data was used construct hydrogeological maps as shown in Figure 8 with all the relevant information like the elevations of the water table and bedrock rock top and thus the thickness of the shallow aquifer. This information is considered as the basic input data for the groundwater flow model which was developed and validated for Wadi Al Bih.

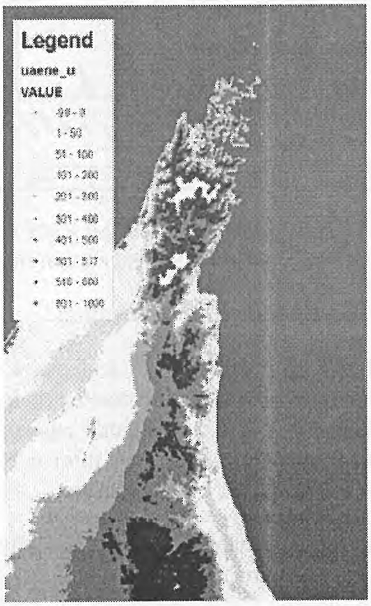


Figure 7: A Shape file of a DEM Model for the Northern Emirates

5. Groundwater Quality

Groundwater in the upper aquifer in Wadi Al Bih is fresh to brackish water with electrical conductivity (EC) is ranging from less than 830 μmho/cm in upstream to 12,410 μmho/cm in the outlet and alluvial fan areas. The measured EC values in the water samples collected from the lower aquifer are ranging from 420 μmho/cm to 830 μmho/cm. It is important to mention that none of the wells located downstream of the dam are tapping the lower aquifer. Thus, the quality of groundwater below a depth of 150 m at the Wadi Al Bih wells is unknown in this part of the area.

Trilinear plot of the chemical analysis of water samples presented in Figure 9a,b shows a high concentration of HCO3 - ions in the upstream wells associated with low total dissolved solids (TDS) values which probably indicates that the water is meteoric and partially derived from rain. In the outlet area (e. g. Burairat well), the samples occupy the upper triangle of the diamond-shaped field which points to the dominance of Na-Mg and chloride water type.

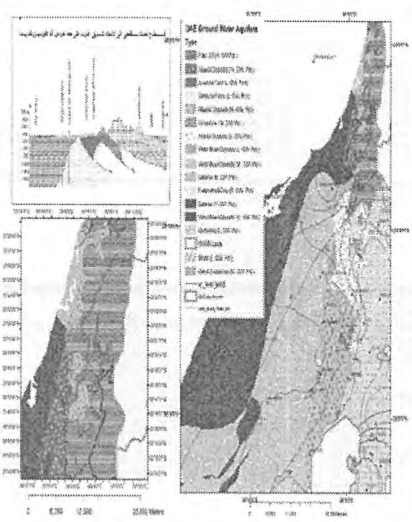
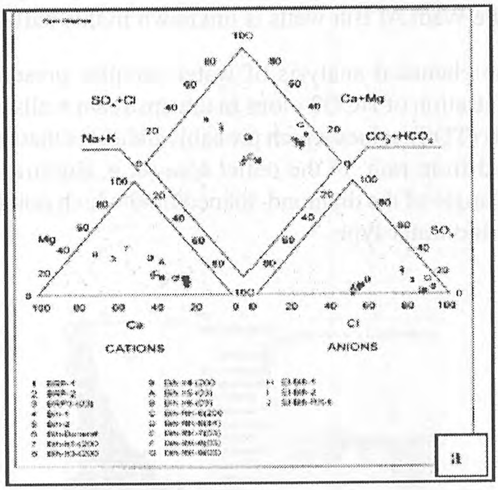


Figure 8: A digital hydrogeological map of UAE (left) with the measured water table contours in Jan. 2005 (orange) and the elevation of the unconsolidated material aquifer bottom above MSL (dark blue). On the right hand side zoom in has been made on the western part of Wadi Al Bih.

The water accumulated in the mountain area underneath Wadi Al Bih and flowing along the valley to the west is enriched with Mg2+ which is dissolved from Mg-rich dolomitic rocks. At the outlet of the wadi groundwater, it is discharged into Jiri Plain, west of the mountain range forming a good aquifer in the Quaternary sediments in contact with the limestone. Near the coast groundwater quality is strongly affected by the sea water intrusion and evaporation in areas where the water table is shallow. As a result, the groundwater became enriched with Na+ and Cl- ions.

Because groundwater in this area is mainly used for irrigation purposes, values of electrical conductivity and sodium adsorption ratio were plotted on Figure 9b. It indicates that groundwater in the main valley of Wadi Al Bih is good for irrigation purposes. In the alluvial fan area groundwater from the upper aquifer can not be used for irrigation purposes.



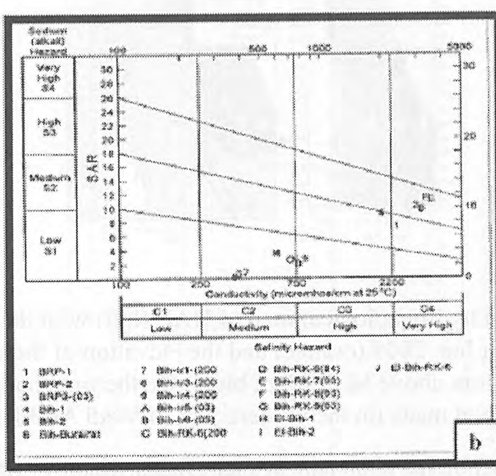


Figure 9 (a, b): Graphical presentations of the hydrochemical analysis data of the water samples collected from some wells in Wadi Al Bih.

6. Conclusions

The Quaternary aquifer is directly recharged from the percolating rainfall. Historical groundwater measurements indicate a significant variation in the response to recharge events and groundwater abstractions from one area to the other mainly depending on its distance from the dam. Wells located in the vicinity of the ponding area on the upstream side of Wadi Al Bih dam are more sensitive to precipitation and recharge events. This clearly indicates that since its construction in, the dam has been playing an important role in the recharge of the shallow aquifer. The results of the chemical analysis of the water samples periodically collected from the monitoring wells indicate that the quality of the groundwater in the study area varies from fresh water (TDS <500 ppm) in the upstream (near well RK-6) to brackish water in outlet area in Burairat (TDS >2000 ppm).

The Quaternary aquifer is currently exploited for domestic and agricultural purposes. On the other hand the bedrock aquifer was only tested in one well (RK-6) and need further detailed study. However, the results of the 2D earth resistivity imaging survey indicate that this bedrock aquifer is probably extending for several hundred of meters and thus constitutes a deep groundwater aquifer with high groundwater potentiality in the areas where it is strongly fractured and karistified. The groundwater quality in this aquifer seems to be very fresh.

The hydrogeological GIS databases offer capabilities for hydrogeological modeling and other hydrogeological studies, including:

1- Automatic data treatment is crucial before input the numerical groundwater flow model. Because of the huge amount of work that is required to prepare the data used in these models, the GIS database is essential.

2- Different types of geopotentail maps of model output can be easily produced using GIS capabilities. Global view of hydrogeological data can be obtained by using the generated maps.

3- Correlation between groundwater hydrochemical parameters, aquifer depth, aquifer lithology, and land-use is possible by using recorded data and statistical package implemented in the GIS software.

4- Groundwater exploration and evaluation studies can be optimized using the dynamic GIS data bases.

5- Groundwater contamination due to salt-water intrusion in the coastal area can be monitored and minimized by using dynamic GIS databases.

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Methods of groundwater recharge estimation in Arid Regions

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METHODS OF GROUNDWATER RECHARGE ESTIMATION IN ARID REGIONS

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ABSTRACT

Groundwater recharge estimation has become a priority issue both in humid and arid regions for water management and conservation, especially in arid regions like the Arabian Peninsula. Numerous methods are being used for recharge estimation, including the water-balance, Darcy's law, soil physics, chloride mass-balance and environmental isotopes technique. One method might be applicable in a certain environment, but proves inappropriate in others. The geologic complexities, lack of information, low rainfall, and the numerous mechanisms interacting to move water through the system pose a challenge to appropriate estimation of recharge. This paper discusses the various methods for recharge rate estimation applied in arid environments, their extent of applicability, with comparisons and contrast.

Keywords: Rainfall, Recharge Estimation, Arid Regions, Arabian Peninsula

Introduction

Water is the primary key factor of life on the Earth. In arid and extremely arid regions, groundwater is a significant part of the total natural resources. Groundwater recharge, the flux of water across the water table, is arguably the most difficult component of the hydrologic cycle to measure (Hogan et al., 2004). Recharge becomes the most significant element after the rainfall occurrence, but its direct calculation is not possible. Hence, the recharge rates in arid regions are small and must be estimated with care and accuracy. Due to the variety of spatial and temporal scale-aquifers, recharge estimation may be required in a time scale ranging from days (in shallow alluvial, fractured and karstic aquifers) to thousand of years (in deep and mine aquifers).

Groundwater recharge rates and mechanisms in arid and extremely arid regions are subject of many techniques and methods all over the world. Different methods can be used to estimate groundwater recharge, such as empirical approaches, water-balance techniques, tracer techniques and others depending on data availability and the field situation (Eagelson 1979; Lerner et al., 1990; Flint et al., 2002; Edmunds et al., 2002; Scanlon, 2004) during the last two decades. Carter et al. (1994) summarized previous rain-fed groundwater recharge studies in semi-arid and arid regions around the world. The groundwater recharge percentages of these studies range from 1 to 30% of the local rainfall. Tracer techniques, such as environmental isotope and chloride mass-balance (CBM), have been commonly used in the overall domain of water resources development and management (Fritz and Fontes, 1980; Wood and Sanford 1995; Wood and Imes 1995; Wood 1999; Shi et al., 2000; Kattan 2001; Scanlon, 2004). In fact, the application of these relatively new techniques has played an important role in solving the envisaged hydrogeological problems that cannot be solved by conventional methods alone. (IAEA, 1980, 1983; Clark and Fritz, 1997).

With the exception of the Arabian Shield and Oman Mountain, the Arabian Peninsula (where there are no perennial rivers or surface water) is characterized by very little, unpredictable , and irregular occurrence of rainfall which may be very intense in local storms. Accordingly, the magnitude and distribution of rainfall vary from place to place and from time to time according to seasonality and topography. Describing and predicting the rainfall variability in space and/or in time are fundamental requirements for a wide variety of human activities and water projects.

Because of rapid economic growth and lack of rainfall in the Arabian Peninsula countries, the use of groundwater resources has increased dramatically. The human activities can be sustained based on a good management of groundwater storage volumes without significant problems. However, recharge rate estimation in arid regions involves a large degree of uncertainty due to low rainfall and high evaporation.

Recharge in the Arabian Peninsula, which has different topographic features, is often considered as the sum of several distinct processes occurring in different areas of the Peninsula. The Arabian Shield, the Oman Mountain and their wadis are viewed as significant sources of recharge due to the orographic and monsoon rainfall effects from the Atlantic and Indian oceans. The rest of the Peninsula receives rainfall from cyclonic storms that penetrate the area from the Mediterranean Sea (Nouh, 1987; ªen 1983; Subyani; 2004). Recharge can either occur through alluvial deposits of stream channels of the Arabian

Shield and Oman Mountains (wadis) or through fractures in the crystalline bedrock. A combination of short and intense mountain storms, topography and limited infiltration capacity of soils results in flash floods and surface runoff (Alehaideb, 1985; Rizk et. al, 1998). In the rest of the Peninsula, the basin floor receives a significantly less amount of rainfall which occurs by convective and cyclonic storms, but covers the vast majority of the land surface. Recharge in these basins is a shallow effect and may be negligible in deep aquifers (Dençer et. al, 1974a; Caro and Eagleson, 1981; Lloyd, 1981; Subyani and [a]en, 1991).

The purpose of this paper is to describe the hydrological features of the Arabian Peninsula and to delineate recharge zones. This study also describes the application of different methods for recharge rate estimation in arid environments, such as the Arabian Peninsula, their extent of applicability, and comparison and contrast of recharge estimates.

Geology of the Arabian Peninsula

The Arabian Peninsula, lying in the southwest corner of Asia, is a huge crust of ancient sedimentary and volcanic rocks, deformed and metamorphosed and injected by plutonic intrusions. Except for the Oman Mountains, the peninsula can be divided into two main structural provinces, the Arabian Shield and the Arabian Shelf. The Arabian Shield, which occupies about one-third of the peninsula, mainly consists of a Neoproterozoic basement complex, with local Tertiary and Quaternary volcanics (Figure 1). The basement rocks suffered a prolonged history of deformation and metamorphism, and were intruded by igneous bodies of diverse ages and compositions. Tertiary and Quaternary basaltic flows and alluvial sediments cover part of the basement complex. (Powers et al., 1966; Brown et al., 1989; Alshanti, 1993).

The Arabian Shelf forms the remaining two-thirds of the peninsula. It lies to the east, north and south of the Shield. Its foundation is a part of the same Precambrian plate that makes up the Shield. On this peneplaned basement lies a sequence of continental and shallow-water marine sedimentary rocks, ranging in age from Cambrian to Pliocene, dipping gentlly away from the shield, and classified into a number of deep sedimentary basins. These sequences of beds dip gently and uniformly toward the northeast, east and southeast away from the Shield. Dips range from about one degree in the older units to less than half degree in the Cretaceous and Eocene beds (Powers et. al, 1963; the Alsayari and Zötl, 1978) (Figure 1).

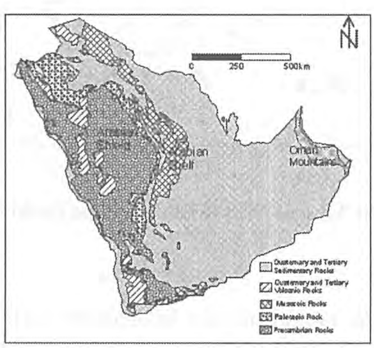

Figure 1. Geologic Framework of Arabian Peninsula.

Hydrology of Arabian Peninsula

In order to assess the groundwater recharge within the basins, it is necessary to define the predominant climate patterns that have an influence on the rainfall distribution over these basins. The study of the water resources in the Arabian Peninsula is the identification of major factors affecting the magnitude and distribution of rainfall, such as altitude, various air mass movements, and distance from moisture source, temperature, pressure, and topography.

The climate pattern over the western province can be best described by considering the various air masses that affect the rainfall distribution over the area considered. The influence of the various air masses and the rainfall pattern over the peninsula were discussed and mapped by several investigators (ªen, 1983; Alehaideb, 1985).

Air masses influencing the peninsula's climate are illustrated in Figure 2. This figure shows that there are three major fronts of moisture flowing into the peninsula. The monsoon (front during the late fall and summer (maritime tropical air mass) reaches the area from south, southwest, and southeast). This front originates from the Indian Ocean and Arabian Sea and brings the warm and moist air. Outbreaks of westerly air become more frequent and are characterized by medium to high intensity of rainfall over the south and southwest of the peninsula. This front often picks up further moisture while moving through the Red Sea trough.

The continental tropical air masses, which are warm and moist, come from the Atlantic Ocean through the middle and North African Continent. The maritime polar air masses are derived from the eastern Mediterranean Sea. During early winter, the Mediterranean-born maritime air increasingly disturbs the monsoonal air movement and displaces it in the low altitudes. Generally, these maritime depressions draw the tropical continental air masses into warm sectors and extreme weather conditions occur, which are associated with the passage of a very warm sector. Both the continental tropical and maritime polar air masses move toward the east and prevail in winter (ªen, 1983; Alehaideb, 1985, Subyani, 1997).

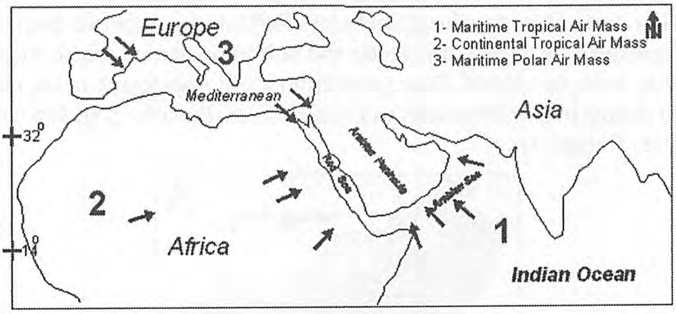

Figure 2: Air Masses Movement Over the Arabian Peninsula

Rainfall

Over the Arabian Peninsula, rainfall is very limited and varies from year to year, but it occurs every season in the mountainous areas. The rainfall often occurs as thunderstorms of very high intensity during a local storm followed by dry periods. As mentioned earlier, autumn rainfall is related to local diurnal circulation, summer rainfalls to the monsoons, and winter and spring rainfalls to the African-Mediterranean interaction. Generally, rainfall in the study area is located under the influence of subtropical and orographic conditions.

The mean annual rainfall distribution map is presented in Figure 3, which shows the spatial variation of rainfall. This figure also reflects the topographic impact; hence annual rainfall generally increases with elevation in Yemen and the Asir Mountains (ranges from 200 to 1000 mm/year). In addition to the winter orographic effect, the monsoon season is a very important factor which gives rise to heavy rainfall in the mountainous area. The rest of the Arabian Peninsula probably has an average annual rainfall of less than 200 mm. Indeed, parts of the vast interior, north and middle of the peninsula receive less than about 100 mm/year. Desert areas have had no rain for periods of several years.

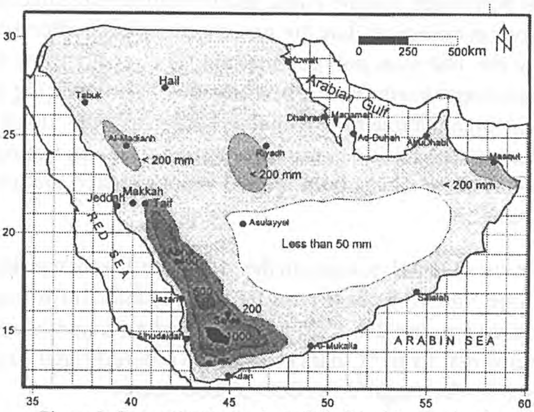

Figure 3: Generalized annual rainfall of Arabian Peninsula.

Recharge Methods Estimation

Groundwater recharge, the flux of water across the water table is arguably the most difficult component of the hydrologic cycle to measure (Hogan et. al, 2004). Recharge becomes the most significant element after a rainfall occurrence, especially in arid regions. Many researchers have applied different approaches to estimate groundwater recharge rates such as empirical approaches, water-balance techniques, tracer techniques and others depending on data availability and the field situation.

Recharge in Deep Aquifers

In central Arabia, where the annual rainfall is around 100 mm, there have been studies estimating the recharge contribution to some deep aquifers such as Minjur, Wasia and Biyadh. Sogreah (1968) estimated very roughly the recharge from the available hydro-climatological data, and they found the recharge rate is about 3-5 mm/year. On the other hand, Dencer et al. (1974b) proposed two distinctive methods in calculating the recharge amount that goes through sand dunes around the Khurais area (100 km east of Riyadh). The first method depends on temperature, and physical properties of the sand and it shows that infiltration from rainfall in the sand dunes is a complex phenomenon. Another method is based on the thermonuclear tritium content of the sand moisture. The authors concluded that the infiltration is about 20 mm/year, and the threshold for this seems to be 50 mm of mean annual rainfall for the recharge to occur.

Furthermore, Sir MacDonald and Partners (1975) estimated the recharge amount through the Wasia and Biyadh formations based on piezometry as well as transmissivity which vary areally and accordingly calculated the average recharge value as 5.2 mm/year. B.R.G.M. (1976) estimated the recharge from the available hydro-climatological data, which were reprocessed for the purpose of numerical model simulations leading to the recharge amount of about 6.5 mm/year. However, Caro and Eagleson (1981) estimated median annual recharge by using a dynamic model of annual water balance with the maximum depth of about 6 mm/year. They conclude that the results quantify the large uncertainty of annual recharge and the importance of considering a variable season length in such arid climate in central Arabia, and also that these deep aquifers are being mined.

Subyani and ªen (1991) developed recharge outcrop relation (ROR) for calculation of the amount of water that percolates into the Wasia and Biyadh aquifers in central Saudi Arabia. The necessary hydroclimatological data are processed with the effective outcrop areas of the formations using the Theisson polygon method. The results show that the amount of recharge is about 4 mm/year. Furthermore, investigations using kriging method of velocity distribution within the area obtained a regional groundwater velocity of 2-3 m/year which compares well with age dating of deep groundwater as shows in Figure 4 (a and b). This means that a water drop takes about 35,000 years to reach the pumping area of the Wasia and Biyadh aquifers.

Lloyd (1981) used environmental isotopes in the east of Jordan for confined and unconfined portions of sandstone and limestone aquifers to provide information for recharge mechanisms. He concluded that due to low rainfall and aridity, recharge from rainfall is rare. He also concluded that from ^{14}C data most of the outcrop waters are modern, but that old waters are present in deep aquifers (6000-20,000 years).

In conclusion, deep aquifers in the Arabian Peninsula that has catchment areas far away from pumping areas such as Saq, Tabuk, Minjur, Wasia, Biyadh, and Umm Er Radhuma are being mined. In addition, previous values of recharge rates obtained by different researchers are only effective in a few meters in the shallow unconfined aquifers.

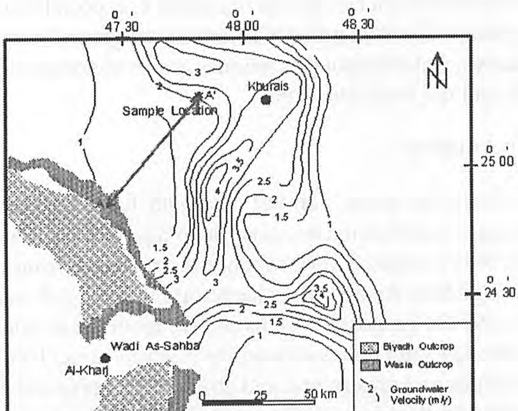

Figure 4 (a): Groundwater velocity map of the Wasia Aquifer.

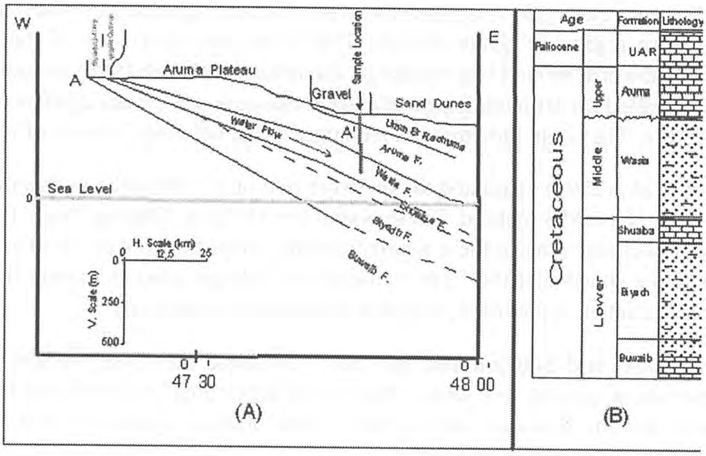

Figure 4(b): (a) Geologic cross-section and water flow, (b) Generalized stratigraphy.

Recharge in Shallow Aquifers

Based on lithologic and morphologic criteria, shallow aquifers can be divided into two main types. The first one is characterized by a certain continuity of characteristics in space, although this can obviously vary with the heterogeneity of the aquifer material and thickness changes of the formation(s) such as wadi alluvium, surface and coastal deposits and basalt flows.

The second type of shallow aquifer can be either crystalline, igneous and metamorphic rocks which are characterized by little or no original permeability but with secondary permeability acquired through fissuring and fracturing. Groundwater resources from these aquifers, derived from recharge or renewable resources consist of that part of the rainfall which infiltrates downwards to supply the aquifers. This infiltration can occur directly, immediately following a period of rainfall, or at a later period from surface waters concentrated by runoff. These resources are dependent primarily on rainfall and secondarily on a series of factors such a lithology, morphology of the drainage basin, fracturing or weathering, depth of the water table and vegetation.

Ghurm and Basmaci (1983) showed that the recharge to rainfall ratio could be as high as 41% in the upstream reaches of the valleys. Also, Basmaci and Al-kabir (1988) noted that deuterium excess in groundwater samples collected from wadis proves recharge from high intensity summer rainfall. Down stream reaches of most of the catchments, which drain to the Red Sea in the west and to middle of the peninsula, are dry. The floods running over steep slopes disappear in alluvial fans. Environmental isotope studies over the coastal area of the Red Sea indicate groundwater ageing exceeding several thousand years (Bosch et al., 1980). Direct recharge of rainfall through fractures is a local phenomena and not significant. Some fracture systems, however, do transfer groundwater over large distances (Basmci and Hussein, 1988). Isotope analysis of some spring water in Saudi Arabia indicated mixtures of water recharged from different sources including present and paleowater (Bazuhair et al., 1990).

Abdul Razzak et al., (1989) applied the water balance approach to Wadi Tabalah in the southwestern region of Saudi Arabia. They estimated that 75% of the rainfall was contributed towards groundwater recharge. Bazuhair and Wood (1996) successfully applied the CMB method for estimating groundwater recharge in some wadi aquifers of the western Saudi Arabia. They conclude that the recharge varied between 3 to 4% of rainfall.

Bazuhair et al., (2002) estimated the recharge rate of six alluvial aquifers of the Arabian Shield using the CMB method. These wadis are Al-Aqiq, Khulais, Wijj, Turabah, Abha and Jizan. Recharge rates to these aquifer systems range from 0.4 to 7% of average annual rainfall. They stated that the large variation in recharge rates is mainly due to rainfall variation and intensity, aquifer properties and climate conditions.

Subyani (2004) and Subyani and ªen (2005) modified the CMB method by including some statistical approaches with effective recharge area and seasonal rainfall. They concluded that the recharge rates in most of the alluvial aquifers in arid regions range from 8 to 10% of effective rainfall.

In conclusion, Shallow aquifers such as wadi deposits, basalt flows and fractured crystalline rocks received a good amount of rainfall that can infiltrate directly to shallow groundwater storage. The rate of recharge depends on hydrological phenomena such as rainfall intensity, runoff, temperature and evaporation, and on physical properties of the aquifer such as porosity, permeability, fracture spacing, surface weathering and watershed properties. In general, the recharge rate in arid regions does not exceed 10%.

Conclusion

Quantifying recharge rates in arid and extremely regions such as the Arabian Peninsula is difficult because of the large variability in topography, geomorphology, geologic complexities, and the numerous mechanisms interacting to move water through the system, lack of information and also spatial and temporal variability in climate and rainfall distributions. Many techniques have been applied in all over the world to evaluate recharge based on physical, chemical, isotopic and numerical modeling approaches. In the Arabian Peninsula, there is not sufficient information to apply such techniques. The following steps should be taken into consideration for recharge estimation.

1- Define the effective recharge area using isotopes techniques (e.g. ä ^{18}O, äD),
2- Define the effective monthly or seasonal rainfall. In other words, in the Arabian Peninsula, only spring and monsoonal rainfall can be used for recharge calculation,
3- The Chloride Mass-Balance method or water table monitoring measurements can be applied after a rainfall event that is not less than 50 mm of monthly rainfall,
4- Due to uncertainties associated with each technique, it is best to apply as many different techniques as possible to better delineate recharge areas, processes and rates.

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Use of “Modflow” for the assessment of recharge contribution to groundwater from a surface irrigation conveyance system

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USE OF "MODFLOW" FOR THE ASSESSMENT OF RECHARGE CONTRIBUTION TO GROUNDWATER FROM A SURFACE IRRIGATION CONVEYANCE SYSTEM

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ABSTRACT

The Rice-Wheat irrigation system has the opportunity to utilize surface water, groundwater and rainwater resources conjunctively. Recent studies have shown that the contribution of groundwater is increasing due to inadequate availability of canal water. As the system utilizes water pumped from the underlying aquifer, a cycle of recharge and withdrawal activities continues. Sustainability of groundwater for the on-going drought in the country depends mainly on the recharge contribution from the irrigation system in addition to other factors. The reported study was, therefore, carried out to measure and assess the recharge contribution from Ghourdour Distributary of Upper Gogera Branch canal irrigation system, Punjab, Pakistan. Assessment of recharge through a distributary was carried out using a groundwater flow "MODFLOW" model, which in turn utilized the observed water table, climatic, crop and soil information for a period of about one year in addition to hydraulic conductivity, evapotranspiration and aquifer characteristics data. The requisite primary data for "MODFLOW" were collected from the field and secondary data from public sector organizations dealing with water. Model calibration involved changing input parameters within reasonable limits until acceptable matches were obtained between the observed and simulated water levels for all observed hydrographs. The external input such as, real recharge through irrigation and precipitation and stresses due to evaporation, later flow and stream were simulated to calculate the monthly water budget of the aquifer. It was concluded that the recharge contribution was 16.5 percent of the inflow rate of the distributary. Using the predicted results of the model (MODFLOW) applied to the distributary, a relationship between recharge (R) and discharge (Q) was also developed. Although, the presented results of recharge contribution were limited to one distributary of the canal irrigation system, yet the developed methodology can be extended to the other canal systems of the Indus Basin.

Keywords: Recharge, irrigation, groundwater, modeling

INTRODUCTION

Canal irrigation was introduced long ago in many developing countries, especially in arid and semi-arid regions. Besides providing water for irrigation, canals also act as a source of recharge to the groundwater. Due to the continuous seepage from the irrigation conveyance system, the water table has gradually risen in some areas over the years. This water table build up has created the problem of water logging and salinity, ultimately leading to land degradation in many regions. On the other hand, rapid extraction of groundwater may lead to excessive lowering of water table and development of secondary salinization due to poor water quality. Groundwater recharge is a critical hydrological parameter that, depending on the application, may need to be estimated at a variety of spatial and temporal scales. Quantification of water fluxes from the atmosphere to the underlying aquifer is important for global water budget. As aquifers are depleting, recharge estimates have become more essential in determining appropriate levels of groundwater withdrawal. Moreover, water loss estimates are essential to water resource assessment and management, which are a function of their availability (Bridget and Peter, 2002).

Agriculture in developing countries utilizes some 80-90 percent of diverted water. The potential for future development of significant amounts of this resource either no longer exists or it is becoming very costly. In view of the global importance of water for food security, major conflicts among the nations are expected just for the access to water (PSF, 1999). The scarcity of water is closely linked to food security. Thus, irrigation has been vital to food security and sustainable livelihood, especially in developing countries. Developing countries are experiencing high rates of population growth, which is putting pressure on available water supplies. Consequently, to feed the growing population, the crop yields need to be increased. The world population is expected to be 8100 million in 2020 compared to the present 5930 million. To meet food requirements in 2020, food production needs to be increased at least 35 to 45 percent (FAO, 1998).

Pumping of groundwater provides a major alternative water resource. About 33% of the world's population depends on groundwater. In many countries, including Pakistan, groundwater is also intensively exploited to supplement surface water from rivers and canals. In Pakistan, the rice-wheat regions are meeting 70 % of their requirements from groundwater. The abstraction of groundwater in general, is approaching its limits in many regions of the world, especially in the drought affected zones. Therefore, sustainability of groundwater resources is needed (Shiklomanov, 1997).

The canal irrigation system in the Indus Basin is facing a number of operational problems resulting in a very high degree of losses of water during conveyance as well as during application of irrigation to crops. These water losses on one hand result in constrained water supplies of canal water but on the other hand provide a source of recharge to the Indus Basin aquifer. Historically, recharged groundwater has been recovered through public and private pumping systems to irrigate crops and meet approximately more than 40% of crop water needs. To provide the sustainable use of groundwater resources, inflow and outflow components of groundwater need to be assessed and analyzed for better management. Kachimov (1992) developed a complex variable method and series expansion for channel bed seepage determination. The method included the standard method of conformal mapping in which expressions of seepage loss from a trapezoidal unlined channel and from a rectangular channel with lined banks were used in the form of dimensionless characteristics. This form of representation offered an opportunity to design the channels for minimum values of loss or the value of a cost function for specified hydraulic characteristics, e.g. area of cross section, hydraulic radius and discharge.

Ghulam and Bhutta (1996) developed a procedure to evaluate recharge from various sources to the groundwater reservoir and to estimate the long term average seasonal groundwater recharge in Rechna Doab of Pakistan. For comparison, recharge was also estimated by the specific yield method from observed groundwater levels. The recharge estimate by the two methods was found to be in good agreement. Punthakey et al., (1996) used a "MODFLOW" model (McDonald and Harbaug, 1988) to find the effect of irrigation on the rise of groundwater in Lower Murrumbidgee, Australia. A finite difference grid of 7500x7500m was imposed on the model area. The contribution from rivers and streams to the groundwater was determined by MODFLOW river package. The model was calibrated using observed potentiometric data from 1980 to 1985. Comparison of contours of observed heads and modeled heads showed that the modeled heads closely matched the observed head contours. Goyal and Chawla (1997) obtained an analytical solution for estimation of seepage from a canal to symmetrically placed drains founded on infinite pervious soil medium and presented it in the form of monographs. Prabhata et al., (2000) found seepage losses from triangular, rectangular and trapezoidal canals by using simplified algebraic equations. A design procedure for triangular, rectangular and trapezoidal canal sections was presented. Using seepage loss equations and the general uniform flow equations, explicit equations for the design variables of minimum seepage loss canal sections were obtained for each of the three canal shapes by applying nonlinear optimization technique.

Osman and Bruen (2002) studied the seepage from a stream, which partially penetrated an unconfined alluvial aquifer. For the case when the water table fell below the streambed level, inadequacies were identified in current modeling approaches to this situation. The suggested technique was incorporated into "MODFLOW" and was tested by comparing its predictions with those of a widely used model "SWMS-2D" (simulating water flow and solute transport in two-dimensional variably saturated media). The suggested technique compared very well with the results of variably saturated model simulations. The proposed method was simple, easy to implement and required only a small amount of additional data about the aquifer hydraulic properties. These studies showed that "MODFLOW" has the potential to predict groundwater fluctuations as a result of seepage from canals and irrigated fields.

In order to manage the groundwater, there was a need to evaluate the potential contribution of various components of irrigation system to the recharge of the Indus Basin aquifer. Therefore, a study was designed to use "MODFLOW" to achieve the following specific objectives:

- To calibrate and validate "MODFLOW" for the aquifer in the command of Ghourdour Distributary.
- To assess the recharge contribution-using modeling approach from Ghourdour Distributary under the given scenario of crop, land and water resources.

Brief Overview of "MODFLOW"

Prediction of recharge from canals and distributaries of an irrigation system requires the use of an appropriate groundwater model. MODFLOW simulates the seepage reliably and runs comparatively more accurately with a minimum available set of data. A brief description regarding the "MODFLOW" model is given below:

"MODFLOW" solves the partial differential equation describing the three-dimensional movement of groundwater of constant density through porous material:

$$\frac{\partial}{\partial x}\left[K_{xx}\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{yy}\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_{zz}\frac{\partial h}{\partial z}\right]-W=S_s\frac{\partial h}{\partial t} \qquad (1)$$

Where,

x, y and z = three dimensional coordinates along the major axes of hydraulic conductivity i.e. K_{xx}, K_{yy} and K_{zz} $[LT^{-1}]$.
h = potentiometric head [L].
W = volumetric flux per unit volume and represents sources and/or sinks of water $[T^{-1}]$.
S_s = the specific storage of the porous material $[L^{-1}]$.
t = time [T].

In general S_s and K_{xx}, K_{yy}, K_{zz} are the functions of space, while h and W are functions of both space and time. Hydrogeologic layers can be simulated as confined, unconfined, or a combination of both. External stresses, such as well or a sink, can also be simulated. Boundary conditions include specified head, specific flux and head-dependent flux. The Evapotranspiration (EVT), River (RIV), Recharge (RCH) and Time-Variant Specified-Head modules have been used in this study. The input data of "MODFLOW" included development of input directory, creation of grids, defining of layer type, transmissivity, boundary conditions, elevation of top and bottom layer, simulation time, initial conditions, horizontal and vertical hydraulic conductivity and effective porosity. The output of the model included the water table elevation at boreholes, recharge contribution to groundwater, evapotranspiration and lateral flow.

MATERIALS AND METHODS

Materials and methods include the description of the study area, collection of data and research techniques. The study comprised field oriented and desktop computer modeling work for the collection and analysis of data. The proposed study focused on the assessment of recharge from the distributary of the irrigation system. Assessment of recharge through the distributary was carried out using a "MODFLOW" groundwater model, which in turn utilized the observed data on water table records, climate, crop and soil. The requisite primary and secondary data on recharge assessment were collected from the field and the concerned national and international organizations.

Study Area

The research was carried out in Rechna Doab, Punjab, Pakistan, which is the interfluvial sedimentary basin between the Chenab and Ravi rivers. Rechna Doab lies between the Longitude 71°- 48′ to 75°-20′ East and Latitude 30°- 31′ to 32°- 51′North. To assess the recharge contribution to groundwater using "MODFLOW" from the distributary of irrigation system, Ghoudour Distributary of Upper Gogera Branch canal in the Rice-Wheat irrigated system of Rechna Doab was selected. The Ghoudour Distributary off takes at approximately 31 km (RD, 101000) downstream of Sagar Head (the beginning of Upper Gogera Branch canal). The designed discharge of Ghoudour Distributary is 1.36m^3/s. Its head regulator is controlled by stop logs and the canal has a length of 20.7 km serving 43 watercourses with a total command area of 8251 ha. The sketch of the selected Ghoudour Distributary is given in Fig. 1.

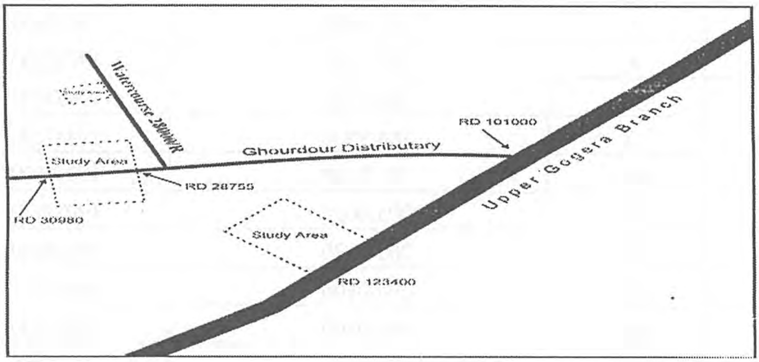

Fig. 1: Sketch of Ghoudour Distributary

Data Collection

Techniques used in this study required field data pertaining to meteorological, hydrological, soil, crops and irrigation. The primary data regarding water table, infiltration rate, hydraulic conductivity, soils textural analysis and flow measurements were collected from the selected site. The data regarding the geometry, water stage and flow rate of the Ghourdour Distributary were collected from Punjab Irrigation and Power Department, Upper Gogera Division, Sheikhupua.

Use of "MODFLOW"to Predict Recharge Contribution

The reach of Ghourdour Distributary between RD 28755-30980 has been selected for the model application. A cross-sectional model was constructed across the Ghourdour Distributary. Transient flow simulation for 12 months from February 10, 2003 to January 31, 2004 (357 days) was used to determine the recharge rate to aquifer system in the left half of the Ghourdour Distributary. The model was calibrated and subsequently, used to predict recharge from the distributary using data collected during the study.

(a) Description of Model Domain

The cross-sectional model grid was 405.33m in length from west to east, consisted of 3 rows, 14 columns and 4 layers. The model grid contained 168 cells, out of which 42 (row-2) were active and 126 (row-l and 3) were inactive. The width of all the cells in all the rows ("y) was 100 m. The lengths of cells of row-2 ("x), their ground surface elevations and initial head values in the cells are given in Table 1. The values of elevation of ground surface and initial head valued as shown in Table 1 were primarily the results of interpolation by the model using the known elevation of ground surface at the boreholes sites observed during the reported study.

Table 1: Length and Elevations of Ground Surface at Cells of Row-2 of the Distributary

Cell No.	Length(m)	Elevation of ground surface(m)	Initial head(m)
1	2.33	205.8500	199.0091
2	5	205.8500	199.0100
3	5	205.8400	199.0000
4	5	204.9200	199.0200
5	5	204.8900	199.0200
6	15	204.9000	199.0200
7	25	205.0100	199.0400
8	25	205.0025	199.0520
9	25	205.0170	199.0600
10	25	205.0106	199.0761
11	67	205.0400	199.1200
12	67	205.9084	199.1454
13	67	204.6014	199.2495
14	67	204.7136	199.2098

Considering the lithology of the profile of the study area, the total depth profile was divided into 4 layers each of 7, 23, 25m and the remaining depth to the bottom of the aquifer as given in Table 2.

Table 2: Thickness of Aquifer Layers of the Distributary

Layer	1	2	3	4
Thickness (m)	7	23	25	From the bottom of 3rd layer to bottom of aquifer

The top layer was unconfined, 2nd and 3rd layers were confined/unconfined (transmissivity is constant) and 4th layer was confined. The transmissivity and storage coefficient were all set to be calculated in the model.

(b) Basic Parameters

The basic parameters for "MODFLOW" at the distributary included number of stress periods and their duration, location of boreholes and observations, horizontal and vertical hydraulic conductivity, specific storage and specific yield, which are summarized below:

- Time: The flow type was transient with time unit in days. Total simulation period was 357 days, (from February 10, 2003 to January 31, 2004), which was divided into 12 stress periods and each stress had one time step. The length of each stress period is given in Table 3.

Table 3: No. of Days in Stress Period

Stress period	1	2	3	4	5	6
No. of days	20	31	30	31	30	31
Stress period	7	8	9	10	11	12
No. of days	31	30	31	30	31	31

- Boreholes and Observations: There were 9 boreholes (piezometers), and the observations of the water table elevation were taken on alternate days. The location of these boreholes is given in Table 4.

Table 4: Location of Boreholes

Borehole No.	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9
Distance from the centre of distr. (m)	5	10	15	20	30	50	90	170	330

- Horizontal hydraulic conductivity of each layer ranged from 10.2 to 100 m/day. Vertical hydraulic conductivity of each layer ranged from 1.04 to 10 m/day as summarized in Table 5.
- Specific storage value for layer 2 was 0.000793 m-1 and 0.000001 m-1 for the other three layers as summarized in Table 5.
- Specific yield values were 0.09, 0.25, 0.25 and 0.25 for layers 1, 2, 3 and 4, respectively as summarized in Table 5.

Table 5: Basic Parameters for the 4 Aquifer Layers

Layer	**Horizontal hydraulic Conductivity(m/day)**	**Vertical Hydraulic Conductivity(m/day)**	**Specific Storage(m^{-1})**	**Specific yield**
1	10.2	1.04	0.000793	0.09
2	100.0	10.0	0.000001	0.25
3	100.0	10.0	0.000001	0.25
4	100.0	10.0	0.000001	0.25

(c) Evapotranspiration Module

The evapotranspiration (ET) surface and extinction depth were selected as 0.5 m below the ground surface and 1.5 m, respectively. The maximum evapotranspiration (ET_m) rates for the 12 stress periods for the distributary are shown in Table 6.

Table 6: Maximum Evapotranspiration Rates from Fields across Distributary

Stress period	1	2	3	4	5	6
ET_m (m/day)	0.00222	0.005219	0.009373	0.013061	0.012895	0.045024
Stress period	7	8	9	10	11	12
ET_m (m/day)	0.006637	0.00635	0.003384	0.002464	0.00167	0.001392

(d) Recharge Module

The sources of recharge to groundwater include infiltration from rainfall, watercourses to the study area and losses from irrigated fields. Recharge was assumed to be uniform for all the cells during a stress period. Recharge fluxes for all the stress periods are shown in Table 7.

Table 7: Recharge Flux to the Aquifer across the Distributary

Stress period	1	2	3	4	5	6
Recharge flux (m/day)	0.00106	0.00074	0.00240	0.00206	0.00217	0.00303
Stress period	7	8	9	10	11	12
Recharge flux (m/day)	0.00245	0.00203	0.00045	0.00055	0.00043	0.00043

(e) River Module

The hydraulic conductance of the riverbed for the cell (1, 2, 1) as shown in Fig. 3.14 was 580 m^2/day for the period in which there was water in the distributary and zero when there was no water in the distributary. Elevation of the distributary bed bottom was 205.97m. The average values of head for all the 12 stress periods in the distributary are given in Table 8.

Table 8: Average Values of Head for 12 Stress Periods in the Distributary

Stress period	1	2	3	4	5	6
Head in the distributary(m)	205.97	206.20	206.55	206.56	206.50	206.52
Stress period	7	8	9	10	11	12
Head in the distributary(m)	206.62	206.65	206.60	206.50	206.54	205.97

(f) Lateral Flow Module

The lateral flow downstream was caused by the cell (14, 2, 1). The cell was simulated with Time-variant Specific Head Module. Water table elevations in borehole B_9 were available for this cell. Start heads and end heads for each stress period for this cell are given in Table 9.

Table 9: Observations at Cell (14, 2, 1) of Distributary

Stress period	1	2	3	4	5	6
Start head (m)	199.25	199.34	199.41	199.52	199.47	199.26
End head (m)	199.34	199.41	199.52	199.47	199.26	198.17
Stress period	7	8	9	10	11	12
Start head (m)	198.17	199.241	199.27	199.29	199.48	199.48
End head (m)	199.24	199.27	199.29	199.48	199.48	199.54

Calibration of Model

To measure the performance of the model, calibrated water levels were compared with the observed water levels for 9 observation bores. The hydraulic conductivity and recharge values were adjusted until reasonable matches were obtained between the observed and simulated water levels for all observed graphs. Figure 2 shows the simulated and observed temporal variation of water table elevation at borehole B_1 located at a distance of 5 m from the centre of the distributary.

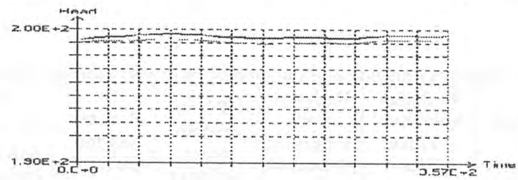

Figure 2: Simulated (bold line) and Observed Temporal Variation of Water table Elevation at Borehole B_1

The results of the calibrated model show that the water levels matched well with the observed water levels. In the piezometer B_1, the modeled groundwater level was consistently higher than the actual groundwater level and the possible reason for such a difference included higher recharge and less groundwater abstraction. The simulated and observed temporal variation of water table elevation at borehole B_4 located at a distance of 20 m from the centre of the canal is given in Figure 3.

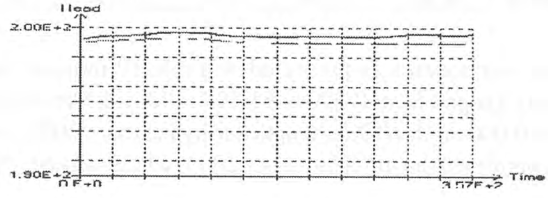

Figure 3: Simulated (bold line) and Observed Temporal Variation of Water table Elevation at Borehole B_4

Figure 3 indicates that the model successfully simulated the water level, which showed an excellent agreement with the observed one. The trend of the observed groundwater graph followed closely the modeled curve. The simulated and observed temporal variation of water table elevation at borehole B_9 located at a distance of 330 m from the centre of the canal is given in Figure 4.

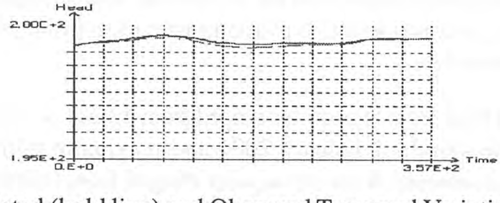

Fig. 3.19: Simulated (bold line) and Observed Temporal Variation of Water table Elevation at Borehole B_9

Figure 4 shows that the model successfully simulated the observed water levels in this borehole since a very close agreement was obtained between the observed and simulated heads. The overall trend of the observed groundwater hydrograph was also followed well by the modeled data.

RESULTS AND DISCUSSIONS

The water balance components as predicted by the model for the stress periods of 1 to 12 are given in Table 10.

Table 10: Water Balance Components of the Aquifer Adjacent to the Distributary

Stress period	Period of analysis	Recharge from distr. (m^3/day/ 100m-length)	Recharge from irrigation & rainfall (m^3/day)	ET from ground-water (m^3/day)	Lateral outflow (m^3/day)	Groundwater storage	
						Released (m^3/day)	Added (m^3/day)
1	Feb-03	00.000	35.863	0.000	+39.552	-	75.413
2	Mar-03	20.700	25.036	0.000	-31.317	-	14.414
3	Apr-03	52.200	67.666	0.000	-82.588	-	37.281
4	May-03	53.100	69.696	0.000	-120.822	-	1.973
5	Jun-03	47.700	73.418	0.000	-137.232	-16.112	-
6	Jul-03	49.500	102.514	0.000	-154.252	-2.237	-
7	Aug-03	58.499	82.891	0.000	-143.534	-2.149	-
8	Sep-03	61.199	68.681	0.000	-129.586	-	0.298
9	Oct-03	56.700	15.225	0.000	-90.198	-18.273	-
10	Nov-03	47.700	18.608	0.000	-55.670	-	10.641
11	Dec-03	51.299	14.582	0.000	-59.160	-	6.686
12	Jan-04	00.000	14.548	0.000	-30.221	-15.673	-

The water balance components as presented in Table 10 indicate that recharge rate from the distributary ranged from 0.000 to 61.199 m^3/day/100m-length. The recharge rate was considered 0.000 m^3/day/100m-length during February 2003, whereas maximum recharge rate was predicted during September 2003, which was 61.199 m^3/day/100m-length.

The recharge from field irrigation and rainfall to the groundwater ranged from 14.548 m^3/day during January 2004 to102.514 m^3/day during July 2003. It was maximum during July 2003, as higher rainfall was observed during this month.

The model predicted the zero evapotranspiration from the groundwater throughout the year. The evapotranspiration surface used by the model was 0.5 m below the ground surface and the extinction depth was 1.5 m as considered for canal recharge analysis. As the water table depth from the ground surface remained greater than 2 m throughout the year, no contribution to evapotranspiration from the groundwater took place during the whole year.

The predicted lateral flow from the aquifer ranged from 30.221 to 154.252 m^3/day. It was minimum during the month of January 2004 and maximum during July 2003. The groundwater storage released from the aquifer ranged from 0.000 to 18.273 m^3/day, whereas groundwater storage added to the aquifer ranged from 0.000 to 75.413 m^3/day.

Recharge Contribution to Groundwater from the Distributary

Using the results of Table 10, the recharge from the distributary was converted to m^3/s/million-m^2. The recharge rate, thus predicted by the model from the Ghourdour Distributary along with the monthly average operational flow rate and stage of the distributary are given in Table 11.

Table 11: Recharge Contribution from the Ghourdour Distributary

Stress period	Month	Flow rate(m^3/s)	Stage(m)	Recharge (m^3/day/100m distr.-length)	Recharge (m^3/s/million-m^2)
1	Feb-03	0.000	0.00	00.000	0.00
2	Mar-03	1.085	0.73	20.700	0.86
3	Apr-03	0.862	0.58	52.200	2.18
4	May-03	0.877	0.59	53.100	2.22
5	Jun-03	0.788	0.53	47.700	1.99
6	Jul-03	0.818	0.55	49.500	2.07
7	Aug-03	0.966	0.65	58.499	2.44
8	Sep-03	1.011	0.68	61.199	2.56
9	Oct-03	0.937	0.63	56.700	2.37
10	Nov-03	0.788	0.53	47.700	1.99
11	Dec-03	0.848	0.57	51.299	2.14
12	Jan-04	0.000	0.00	00.000	0.00
Average for left half side	-	0.748	0.50	41.550	1.74
Total for thedistributary	-	0.748	0.50	83.100=(41.55 x 2)	3.48=(1.74 x 2)

Table 11 shows that the operational flow rate through the distributary ranged from 0.788 to 1.085 m^3/s during the observation period. During the months of February 2003 and January 2004, the seasonal canal closure was observed and consequently, there was no flow in the distributary. The average monthly flow rate through the distributary for the modeled year was 0.748 m^3/s.

The predicted recharge rate results as presented in Table 11 show that monthly recharge rate from the distributary ranged from 0.00 to 2.56 m^3/s/million-m^2 from the left half side of the distributary. The minimum recharge rate (0.86 m^3/s/million-m^2) during the operation of the distributary was predicted for the month of March 2003, as the flow started after the canal closure. The maximum recharge rate was predicted during the month of September 2003, which was 2.56 m^3/s/million-m^2. The average monthly recharge rate for the distributary was 83.100 m^3/day/100m-length or 3.48 m^3/s/million-m^2. The recharge contribution to groundwater was 16.5 percent of the inflow rate at the head of the distributary.

Recharge-Flow Rate Relationship for the Distributary

The relationship between "MODFLOW" model predicted results of the recharge contribution to groundwater and the flow rate through the distributary was developed as given in equation 2.

(2)

Where;

R = recharge contribution to groundwater (m^3/s/million-m^2).
Q = flow rate through the distributary (m^3/s).

CONCLUSION

The monthly recharge rate from the distributary ranged from 0.00 to 2.56 m^3/s/million-m^2 from the left half side of the distributary. The minimum recharge rate (0.86 m^3/s/million-m^2) during the operation of the distributary was predicted for the month of March 2003, as the flow started after the canal closure. The maximum recharge rate was predicted during the month of September 2003, which was 2.56 m^3/s/million-m^2.The model predicted the average monthly recharge rate for the distributary to be 83.100 m^3/day/100m-length or 3.48 m^3/s/million-m^2.The recharge contribution to groundwater was 16.5 percent of the inflow rate at the head of the distributary.

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A sustainable approach for supply augmentation through integration of two non-conventional water resources

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A SUSTAINABLE APPROACH FOR SUPPLY AUGMENTATION THROUGH INTEGRATION OF TWO NON-CONVENTIONAL WATER RESOURCES

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ABSTRACT

The aim of this paper is to reveal the possibility of harnessing the less provoked non-conventional water resources for supply augmentation. In most of the developing countries, continually deteriorating water resources and increasing rate of urbanization has caused a mismatch between supply and demand. It is very difficult to find potable water in the right places and in a plentiful amount in Nepal. However, Nepal receives 1200 mm rainfall annually and many parts are manifested by dense fog. A study was conducted at a fog collection site in eastern part of Nepal. The villagers fetched water from 500 m downhill spending 2 hours time, and about US$ 1.20 per day if they hired strong men. The village observed about 192 days and 70 days of fog and rainfall incidences respectively. The site observed 2.5 m^3 fog water/m^2 of collector area per year and 1.2 m^3 rainwater/m^2 of roof area per year. Therefore, an attempt was made to develop a suitable water collection model to make best use of fog and rain. After trading off between the available supply, demand, storage capacity and cost, a dual supply system was designed to provide 15 liters per capita per day (lpcd) water throughout the year with storage of 17000 liters for a 7-member family. The water quality analysis ensured that it was safe for drinking, and did not deteriorate during long- time (4-6 months) storage in closed containers. Analyses indicated that this integrated system is reliable, cost effective and community manageable. The design period of the system was 10 years. Now, the villagers get water at their house premises. This model gave an extra supply of 3.75 m^3/2m^2 of area/year at a cost of US$ 2.80/m^3 in addition to other conventional sources. The same system could be used for backup supply, groundwater recharging, or for other non-domestic purposes.

Keywords: Rainwater, Fog water, Harvesting, Standard Fog Collector, Roof catchments, Water quality, Supply augmentation, Community, Sustainable.

1. INTRODUCTION

1.1 Overview

Being one of the world's poorest countries, Nepal also suffers many setbacks in developing infrastructure. One of the basic needs is safe drinking water facilities. By the end of the Ninth Development Plan (1997 – 2002), only 71.8% of the total population had access to safe drinking water and only 20% had sanitation facilities. The government is committed to achieve 100% water supply coverage and 50% sanitation coverage by the end of the Twelfth Development Plan (2013 – 2017).

People living in the study area suffered because there were no water sources other than rain or fog. They had to fetch water from far distances that cost them more than two hours a day. Mainly, the burden of fetching water is born by women and children. Travelling was very difficult because of steep slopes. Plagued by this problem, some villagers had even hired porters to carry a can of 16 litres of water for NRs 30.00 (US$ 0.4). For a single day, they had to spend NRs 90.00 (US$ 1.20). Such hardships urged them to look into other alternatives such as fog and rainwater harvesting since they could collect it at their house premises. One can imagine about the hardships by looking at the picture shown below.

Figure 1: A girl child carrying water can on her back

1.1 Background

The aim of this paper is to reveal the possibility of harnessing non-conventional water resources for drinking water supply. Recent experiments with fog and rainwater harvesting technologies indicate that it is a potential source for drinking water at places where rain and persistent moving fog prevails [10]. Therefore, a first ever research study (UNICEF and the WHO Offices at Kathmandu provided the financial support [12]) was initiated in 2002 at a fog collection site in the Dhankuta district of Nepal. The study site is located at an elevation of 1980 m from mean sea level, and coordinates of N 26° 42' W 87° 24'.

The site on a ridge top frequently covered with advected orographic clouds. The average annual rainfall here was 1100 mm, and the temperature ranged between 5°C to 30°C. Humidity varied between 57% in March to 93% in October. There is a near persistent light breeze (speed up to 4 in Beaufort scale [3]). Sometimes storms also hit this area during March.

2 APPROACH AND METHODOLOGY

This study was based on field level observations made at the project site. The Fog Collection Pilot Project was implemented by the Nepal Water for Health (NEWAH) with technical and financial assistance from Canada. The hydro-meteorological observations were booked at the site. The fog and rain collection data were used for analysis and project design. Water quality parameters were examined during the site visit, and all the water quality analyses were completed in the laboratory at the Institute of Engineering, Lalitpur, Nepal. High precision digital instruments were used to measure the temperature, humidity, wind parameters, and pH.

3 ANALYSIS AND SYSTEM DESIGN

The basic concept of a fog water collection process is not complicated. A vertically mounted fog collector screen made up of polypropylene mesh is placed perpendicular to the direction of the moving fog where the tiny water droplets present in fog are trapped. Several droplets are impacted on the mesh and combine to form larger drops, which fall by gravity into a storage tank through a trough placed horizontally at the bottom of the screen. The size of a fog drop is about 1 μm - 40 μm, and a raindrop about 0.5 mm - 5 mm [3]. Fog water and rainwater was collected through double layered Coresa mesh and Corrugated GI sheet roof catchments respectively, and stored to a common tank. For initial assessment of fog yield, a 1m x1m Standard Fog Collector (SFC [10], see Figure 5) is placed at the site for one full year. If the yield is promising, then the Long Fog Collectors (LFCs) are used for actual extraction of water. It is also a good collector of rainwater. To capture more water, the number of LFC is increased. The size of a LFC is 4m wide by a variable length up to 20m. Generally, the life of the mesh is about 10 years [2].

A dual supply system capable of collecting both fog and rainwater was designed for a community of 73 people (13 households) with an annual growth rate of 2.2%. The design period was 10 years. The daily average fog water collection in different months [9] is shown in Figure 2.

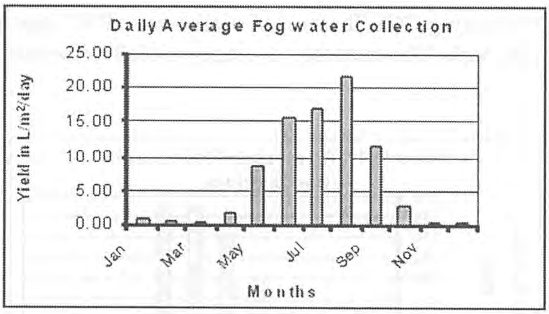

Figure 2: Daily average fog water collection rate

The National Drinking Water Guidelines of Nepal prescribes the average daily water demand for rural community to be 25-45 Lpcd from conventional sources. However, a community level survey at the site revealed that 14 Lpcd was just enough. Hence, a combined demand of 15 Lpcd was adopted. Out of 15 liters, 9 liters were tapped from fog and the remaining 6 liters from rain sources. The calculations of mesh area, roof area, and storage capacity, were based on the need of a single-family system. The calculated average daily fog yield of 6.75 L/m^2/day was taken for analysis.

3.1 Collector Mesh Area Calculation

Theoretical mesh area (S_t) required is based on the water demand, and the actual required area (S_a) corresponds to the amount of water effectively captured by physically available mesh in a given moment [1]. The mesh areas were calculated by using Equations (1), (2), (3) and (4).

$$S_t = \left(N \times C_p\right) \div V \quad (1)$$

$$S_a = S_t \div (DF \times E) \quad (2)$$

$$DF = \left(1 - C_m / C_t\right) \times 100 \quad (3)$$

$$E = \left(1 - Dev.std./V_c\right) \times 100 \quad (4)$$

Where:

N = population that the project should supply

C_p = daily water demand in L/capita/day

DF = physical availability (%), corresponds to actual daily available mesh area actually capturing

C_m = collectors in daily maintenance program

C_t = total number of collectors

E = efficiency of the system in percentage. It is the percentage of variation of the standard deviation, with respect to the median of the average volume of water V_c in L/m^2/net/day collected in the area under study.

The rain was collected using CGI Sheets roof catchments, PVC pipe gutters and pipes, and a plastic storage tank. The monthly average rainfall collection [6] is shown in Figure 3.

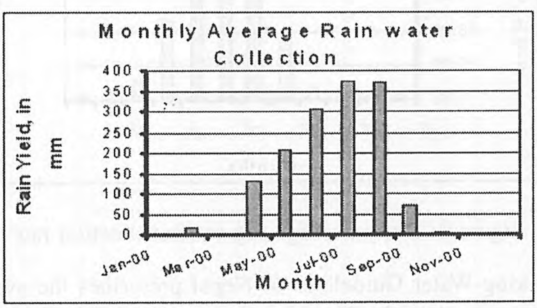

Figure 3: Monthly average rainfall rate

3.2 Roof Catchments Area Calculation

Similarly, the monthly rain collection was calculated using rational Equation (5).

$$Q_s = (0.992 \times C \times I \times A) \quad (5)$$

Where,

Qs = monthly amount of water collected from roof catchments in liter
C = coefficient of runoff. For CGI roof counting the minor losses through evaporation, leakage from gutter and dispersion (C = 0.85 adopted)
I = monthly average rainfall in mm.
A = area of roof catchments in m2

3.3 Storage Size Calculation

The calculation of storage capacity was determined by using the following Equation (6) [4].

$$V = MCS + MCD - (TS - TD) \quad (6)$$

Where,

V = Volume of storage tank in liter.
MCS = Maximum Cumulative Surplus in liter.
MCD = Maximum Cumulative Demand in liter.
TS = Total Supply in liter.
TD = Total Demand in liter.

Storage capacity was designed so that there was no surplus supply and no demand deficit in the total cycle. The final storage required per house was 17000 L. The corresponding required mesh area and roof area were $12m^2$ and $12m^2$ respectively to cater to a daily demand of 15 Lpcd. However, the storage capacity was reduced to 3000 L when seasonal storage (for 6 months) was provided, other factors remained the same.

4 COST OF THE SYSTEM

For analysis purpose, mesh screen with all necessary pole-mounting accessories, complete roof structure, gravity spring intake Type-IA with protection, and the required storage were considered because they are the major cost- bearing and cost- varying components. The costs were calculated using the actual costs at site with rates applicable for year 2002. Therefore, only the costs of these components were used for the analysis [4]. The component costs of different supply systems are shown in Table 1.

Table 1: Components cost matrix

Type of Supply System	Cost in US$
Coresa mesh with pole mounting and anchorages	$8.50/m^2$
26 Gauge CGI Sheet Roof with wood rafters,purlins,etc.	$2.00/m^2$
Gravity Spring Type-IA Intake with collection chamber	773.00/ unit

5 WATER QUALITY

Examination of some water quality parameters for both fog and rainwater indicated that the collected water could be used for drinking. Many studies, in Nepal, on stored rainwater quality confirmed that it is safe. Moreover, this study also ensures that fog and rainwater are safe to drink and the community has accepted it as well. Rainwater and fog water is characterized by low mineral contents and low pH values [8]. However, studies have shown that pH, alkalinity and hardness increases when stored in a cement concrete tank for 3-6 months, which also improves the taste of the rainwater. The fog (in August) and rainwater (in July) quality parameters examined are presented in Table 2.

Table 2: Observed fog and rainwater quality

S.No.	Parameter (Fog)	Value	Parameter (Rain)	Value
1	Water temperature °C	15.25	Water temperature °C	21
2	Conductivity, μS/cm	278	pH	6.8
3	pH	5.55	Color	clear
4	Color	clear	Taste	palatable
5	Taste	palatable	Turbidity, NTU	<5
6	Turbidity, NTU	<5	Free chlorine, mg/l	10-12
7	Chlorides, mg/l	none	Total hardness, mg/l	12-14
8	Total hardness, mg/l	24	Alkalinity, mg/l	21
9	Alkalinity, mg/l	26 (HCO_3^- only)		
10	Relative humidity, %	78		
11	TDS, mg/l	178		

6 CONCLUSION AND RECOMMENDATIONS

From technical and cost analyses of different water supply options, it was the combined fog and rainwater harvesting system that costs the least (US$ 968) compared to others. Table 3 represents the total costs of four different technology options.

Table 3: Collection system costs matrix

S.No.	Collection System	Components	Cost in US$
1	**Fog watercollection**	Mesh 16m²	136
		Roof	-
		Storage 19m³	970
		Total	1106
2	**Gravity (surface)collection**	Intake,TP-IA	773
		Roof	-
		Storage 1m³	224
		Total	997
3	**Rainwater collection**	Mesh	-
		Roof 32m²	64
		Storage 20m³	981
		Total	1045
4	**Proposed combinedcollection**	Mesh 12m²	102
		Roof 12m²	24
		Storage 17m³	842
		Total	968

Analysis indicated that fog water yield per m^2 at the site is double that of the rain water (i.e. 2.5 m^3/m^2/year and 1.2 m^3/m^2/year respectively). Observed fog period was about 192 days, and a maximum daily fog water collection up to 118 $L/m^2/d$ was recorded [9].

Therefore, in terms of quantity, quality, and cost the proposed model [4] as shown in Figure 4 was an appropriate alternative technology solution that could be managed and maintained by rural communities having similar site conditions. Due to page limit, construction modalities, community acceptance and participation, community awareness and action plan, and operation and maintenance aspects have not been discussed in this paper. Such a system may be used as an augmented or backup supply, reserved emergency supply, and for groundwater recharging. Use of bleaching powder is advisable to control contamination.

Advantages

The fog and rainwater collection system has the following advantages.

- Quick and simple design and construction.
- Modular system that can grow in line with demand or available funds
- Passive collection system requiring no energy input to operate
- Cheap and easy to maintain and repair
- Multiple use of water for domestic, irrigation, livestock, reforestation
- Water quality is generally good in non-industrial areas, though pH is low

Disadvantages

The disadvantages of the fog collection system are:

- Technology requires very specific climatic and topographic conditions.
- Yield is difficult to predict.
- Yield is very sensitive with changes in climate.
- It requires full community participation.

In the Sultanate of Oman, a fog collection experiment was conducted during 1989 and 1990. Monsoon in Oman occurs in mid-June to mid-September. The average collection rate was very good at 30 $L/m^2/d$ for 3 months at an elevation of 900-1000m [7]. The largest fog collection project in Chile yielded 5.3 – 13.4 $L/m^2/d$ at an elevation of 780m [5]. In the Arabian Peninsula, the fog collection technology has been used recently in Yemen [11] (Shamsan, Saada, Hajja Governorates), and the Sultanate of Oman (Dhofar regions). Recently, the fog collection projects have been successfully implemented in South Africa, Guatemala, Bolivia, Colombia, Peru, and Namibia, other countries such as Sudan, India, Canary Islands, Venezuela, Pakistan, Angola, Morocco, Kenya, and the Arabian Peninsular regions, China, Hindu-Kush regions are also the potential areas for this technology application. However, we need to conduct experiments to find out such possibility in other parts of the globe.

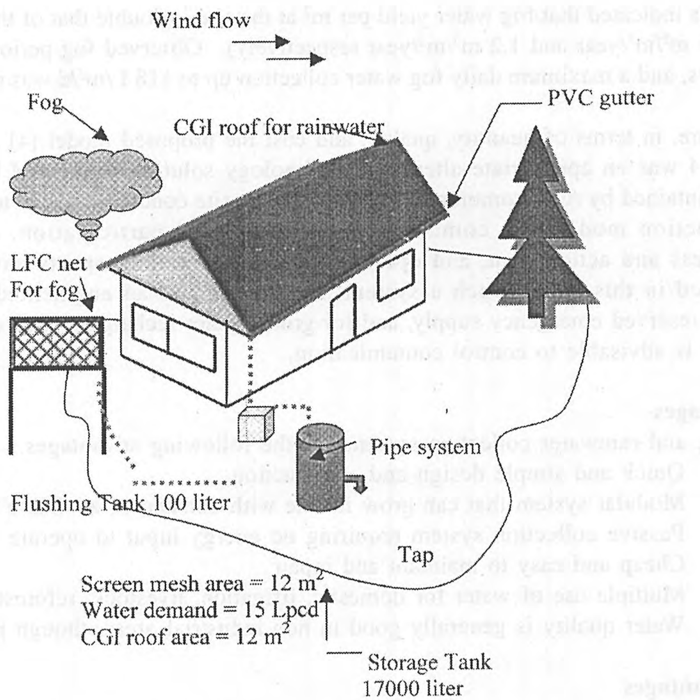

Figure 4: Rural Model House with Fog and Rainwater Collection System

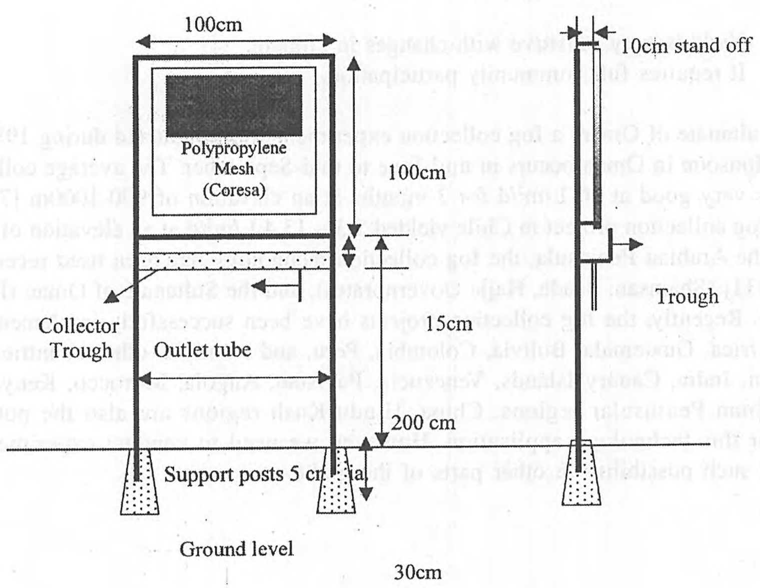

Figure 5: Standard Fog Collector (SFC)[1] unit & its details

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Use of Environmental Tracers to identify and date recent recharge to the surficial Aquifer of northeastern Abu Dhabi Emirate, United Arab Emirates

Robert B. Symonds, Armando R. Robledo, Hussein, H. Al-Shateri

USE OF ENVIRONMENTAL TRACERS TO IDENTIFY AND DATE RECENT RECHARGE TO THE SURFICIAL AQUIFER OF NORTHEASTERN ABU DHABI EMIRATE, UNITED ARAB EMIRATES

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ABSTRACT

Seventeen wells located near Al Hayer and in the Al Jaww Plain of northeastern Abu Dhabi Emirate were sampled to determine the age of recent recharge to the surficial aquifer using the environmental tracers CFC-11, CFC-12, CFC-113, and SF_6. All ground-water samples showed CFC-113 contamination, possibly caused by well drilling and casing materials. CFC-11 model-recharge dates were 2-8 years older than the CFC-12 and SF_6 model-recharge dates, possibly because of the equilibration of recharging water with old air in the unsaturated zone. CFC-12 and SF_6 appear to be the most reliable environmental tracers for dating recent recharge to the surficial aquifer. Air sampling indicates that concentrations of CFC-12, CFC-113, and SF_6 in air of eastern Abu Dhabi Emirate are similar to those in North American air at Niwot Ridge, Colorado. Sources of recharge to the surficial aquifer include rainfall on gravel plains, infiltration of surface water when wadis flow because of rainfall in the Oman Mountains, and lateral flow of ground water from upgradient recharge along the mountain front. The calculated average age of ground water in the surficial aquifer near Al Hayer and in eastern Al Jaww Plain ranges from 12 to 45 years. Ground-water age may increase with distance from the mountain gaps and in some places increases with depth. Calculated average model-recharge dates indicate episodes of major recharge occurred in 1956, 1962, from 1968 to 1969, from 1972 to 1974, 1983, and from 1986 to 1989. Recharge can occur after large rainfall events and after successive long-term moderate rainfall events. Episodic recharge is consistent with the highly variable annual rainfall and frequent periods of little to no rainfall in the Eastern Region of Abu Dhabi Emirate.

Keywords: CFC, age-dating, SF_6, recharge, ground water.

Introduction

Although desalination plants supply an increasing fraction of water needs in the United Arab Emirates (UAE; fig. 1), ground water remains critical to supply the increasing agricultural, domestic, and industrial demands for water. This resource is being depleted in the Eastern Region (eastern one-third) of Abu Dhabi Emirate (United Arab Emirates University, 1993; Alsharhan and others, 2001).

Understanding natural recharge is vitally important to properly manage ground-water resources in Abu Dhabi Emirate. Previous work on the regional hydrogeology (Imes and others, 1993, and Bright and others, 1996), and on tritium (^{3}He) and carbon-14 (^{14}C) dating of ground water in the surficial aquifer (Alsharhan and others, 2001; Wood and Imes, in press) suggests that most recharge occurs in northeastern Abu Dhabi Emirate adjacent to the Oman Mountains. Tritium concentrations in ground water sampled from some wells along the Oman border is 5 to 10 tritium units (TU). These values are similar to recent rainfall, which provides qualitative evidence for recent recharge. The tritium analyses cannot be used to specifically determine where recharge occurs, the age of ground water in the aquifer, or the frequency of large recharge events. To better understand natural recharge, and identify and date recent recharge to the surficial aquifer of northeastern Abu Dhabi Emirate, the National Drilling Company – U.S. Geological Survey Ground-Water Research Program (NDC-USGS GWRP) began a recharge study in 2001. This study is the first known study to date recent ground-water recharge to the surficial aquifer.

The success of the tritium investigations suggests that chlorofluorocarbon (CFC) and sulfur hexafluoride (SF_6) dating methods might help determine the absolute age of recharge in northeastern Abu Dhabi Emirate. These CFC dating methods are accurate in dating water between 1950 and present (2005) (Plummer and Busenberg, 1999), and the SF_6 dating method is accurate in dating water between 1970 and present (2005) (Busenberg and Plummer, 2000). In this study, CFCs and SF_6 are used to identify and date recent recharge by studying ground-water samples from 17 wells in likely recharge areas. One potential limitation of using CFC and SF_6 ground-water age dating techniques in the Arabian Peninsula is that the established dating procedures are linked to the average composition of North American air (N.A. air) as sampled at Niwot Ridge, Colorado (Maiss and Brenninkmeijer, 1998; Busenberg and Plummer, 2000). Therefore, air samples also were collected from near likely recharge areas in the Oman Mountains in the Al Hayer and Al Jaww Plain study areas (fig. 1) to compare with air from Niwot Ridge, Colorado. Selected wells also were sampled for the dissolved gases nitrogen (N_2), oxygen (O_2), carbon dioxide (CO_2), argon (Ar), and methane (CH_4) to estimate the temperature of recharge, a requisite parameter for determining ground-water age using CFCs and SF_6. These are the first published results for the age of ground water in Abu Dhabi Emirate in close proximity to the Oman Mountains, the concentrations of dissolved gases in the ground water, and the atmospheric concentrations of CFCs and SF_6 in the Arabian Peninsula.

Hydrogeologic Setting of Abu Dhabi Emirate

The surficial geology of Abu Dhabi Emirate consists of (1) the coastal region of tidal flats, sabkhas, and terraces along the Arabian Gulf, (2) the internal sand-dune region covering most of the Emirate, and (3) the piedmont plain near Al Ain (United Arab Emirates University, 1993). Across the northeastern border lie the central Oman

Mountains, which rise from 1,200 to 1,600 meters (m) above sea level and are dominated by mafic to ultramafic volcanic and plutonic rocks of the Semail Ophiolite. Thick sequences of carbonates, clastic sedimentary rocks, and evaporites dominate the geologic framework of Abu Dhabi Emirate (Alsharhan and Nairn, 1997; Alsharhan and others, 2001).

The principal aquifer underlying Abu Dhabi Emirate is composed of surficial sediments. In the study areas, the surficial aquifer consists of Recent eolian sands and sabkha deposits, Quaternary alluvium, and Miocene clastic and carbonate sediments that connect laterally and vertically to form the aquifer. The surficial aquifer generally is unconfined, although confined conditions are present in some areas. Basal confining units of Tertiary and Pre-Tertiary deposits limit the most productive part of aquifer to about the upper 100 m of more-permeable sediments; however, the aquifer thickness can vary from about 30 m to about 200 m. Early investigators of ground-water resources in Abu Dhabi Emirate discovered that the surficial aquifer near Al Ain is one of the main sources of fresh ground water, but warned that this aquifer has limited natural recharge and can be affected by pumpage (Sir Alexander Gibb and Partners 1969, 1970; Hydroconsult, 1978). Over exploitation remains a major threat to the aquifers underlying Abu Dhabi Emirate.

Most of the modern natural recharge to the surficial aquifer is directly associated with the higher precipitation near the Oman Mountains (fig 1). The main recharge mechanisms are (1) infiltration of periodic surface flow along wadis that drain the Oman Mountains, (2) subsurface inflow from lateral flow in alluvial channels at the mouths of drainage basins (gaps) along the mountain front, and (3) from lateral flow through fractured bedrock along the mountain front (Imes and others, 1993, Oskerkamp and others, 1995, and Bright and others, 1996). With mean annual rainfall in the Emirate between 40 and 100 millimeters (mm) per year (United Arab Emirates University, 1993) direct infiltration of rainfall probably provides minor quantities of recharge to the surficial aquifer in interdunal areas throughout Eastern Abu Dhabi Emirate.

Description of Study Areas

Ground-water samples used in this study of ground-water age were collected from wells in the vicinity of Al Hayer and from wells in the Al Jaww Plain in northeastern Abu Dhabi Emirate. In this region of Abu Dhabi Emirate, the Oman Mountains grade westward into a piedmont plain, which is more extensive south of Al Ain than north of Al Ain. Numerous wadis flow into the piedmont plain through gaps in the mountain front. Extensive dune fields cover much of this alluvial surface west of the mountain front. Ground-water flow through the surficial aquifer is to the west away from the Oman Mountains towards the Arabian Gulf (fig. 1). Ground-water levels in the Al Hayer area are about 240 to 260 m above sea level, and ground-water levels in the Al Jaww Plain area are about 340 to 380 m above sea level. The average thickness of the Quaternary alluvium in the study areas is about 30 m and specific yield is estimated to be about 10 to 15 percent. The median transmissivity of the surficial aquifer in Abu Dhabi Emirate is 270 meters squared per day (m^2/d). The transmissivity of the aquifer at 27 of 60 wells tested in the Eastern Region of Abu Dhabi Emirate exceeded the median value. Aquifer transmissivity in the Al Hayer area (from 250 m^2/d to 1000 m^2/d) generally is larger than aquifer transmissivity in the Al Jaww Plain area (less than 250 m^2/d), with the exception of aquifer transmissivity at GWP-17 (7,700 m^2/d) and GWP-18 (3,300 m^2/d) (Bright, D.J. and others, 1996).

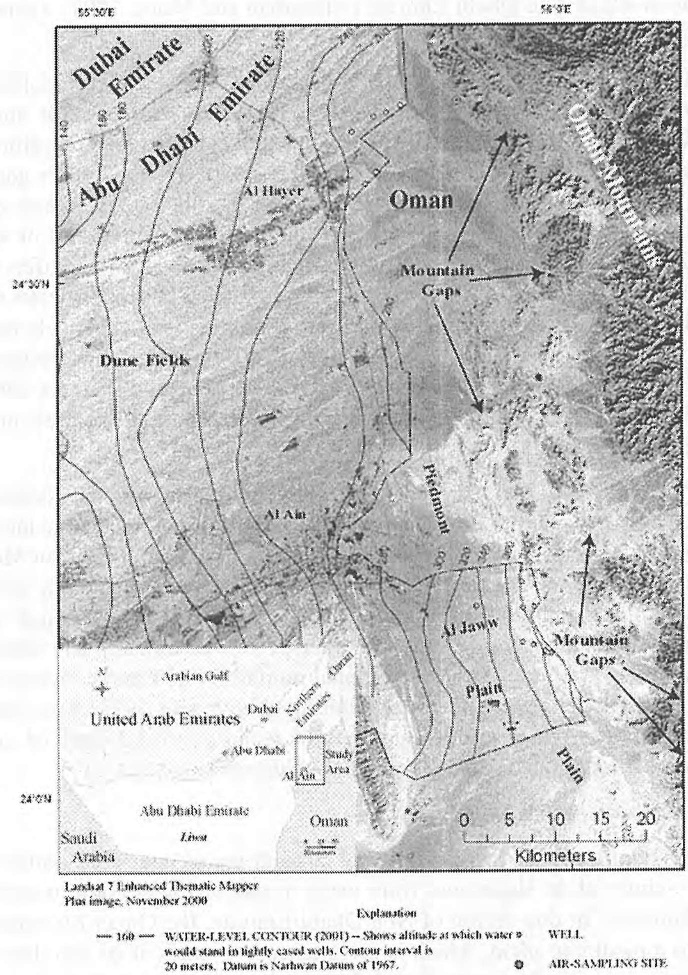

Figure 1. Location of study area within the UAE and locations of sampled GWRP wells and air-sampling sites, and 2001 water-table elevations in the surficial aquifer.

In the Al Hayer study area, active wadis and ancient buried paleochannels that drain the Oman Mountains are buried beneath dunes. Four wells (GWP-228, GWP-235, GWP-236, and GWP-237B) along Wadi Mugayrah and three wells (GWP-343B, GWP-352, and GWP-353A) along Wadi Sinebil were sampled in this area (fig. 2a). Recharge at Wadi Mugayrah, a paleochannel, can occur from surface flow, however, sand dunes prevent surface water from flowing westward to Al Hayer. In contrast, Wadi Sinebil is a large active wadi not covered by dunes. Recharge at Wadi Sinebil may occur from lateral subsurface flow through the alluvium beneath the wadi or from infiltration of surface flow along the wadi after large rainfall events.

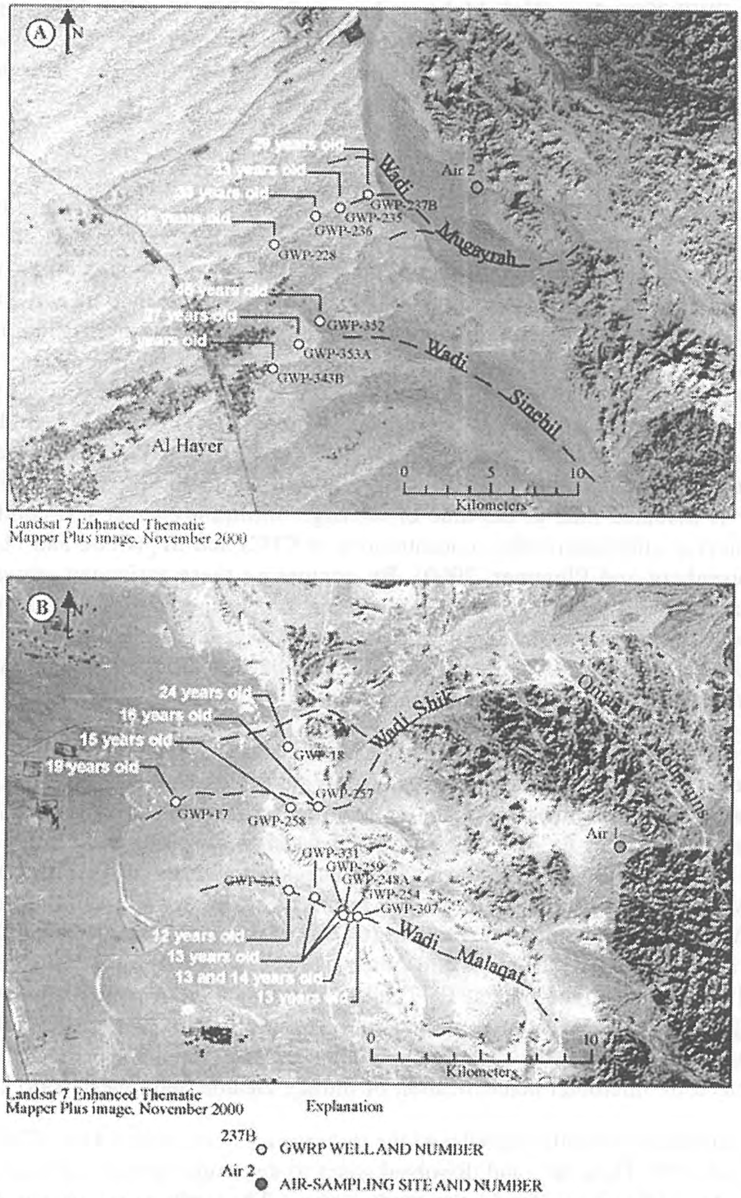

Figure 2. Location of study area, sampled Ground-Water Research Program wells, air-sampling sites, and ground-water ages in the vicinity of Al Hayer (A) and Al Jaww Plain (B).

The Al Jaww Plain study area is a flat, featureless plain of coalesced alluvial fans (fig. 2b). Several wadis enter the eastern edge of the plain through gaps in the mountain front. The main recharge mechanisms to the area are lateral subsurface flow in the alluvium through the gaps, and infiltration of surface flow along wadi channels after large rainfall events. To investigate the ground-water age at various points along the east-to-west flowpath, six wells (GWP-248A, GWP-254, GWP-259, GWP-307, GWP-

331, and GWP-333) along Wadi Malaqat, three wells (GWP-17, GWP-257, and GWP-258) along the southern branch of Wadi Shik, and one well (GWP-18) between the northern and southern branches of Wadi Shik were sampled (fig. 2b). All wells are screened in the upper portion of the surficial aquifer.

Methods and Sampling Procedures

CFCs and SF_6 have been developed as dating tools of young ground water because (1) their atmospheric concentrations have increased rapidly over the past 50 and 30 years respectively, (2) their atmospheric concentrations over the past 50 years have been established, (3) their solubility relations in water are known, and (4) their concentrations in air and ground water can be accurately measured (Plummer and Busenberg, 1999; Busenberg and Plummer, 2000). The main CFC compounds used in ground-water dating are CFC-11 ($CFCl_3$), CFC-12 (CF_2Cl_2), and CFC-113 ($C_2F_3Cl_3$). These compounds can be used to date waters recharged since 1941, 1947, and 1955, respectively (Plummer and Busenberg, 1999). SF_6 can be used to date waters recharged since about 1970 (Busenberg and Plummer, 2000). With these dating methods, it generally is assumed that, at the time of recharge, infiltrating water last equilibrated with air having atmosphere-like concentrations of CFCs and SF_6 (Cook and Solomon, 1995; Busenberg and Plummer, 2000). By comparing these estimated atmospheric concentrations with historical atmospheric data, and by making some assumptions about the flow regime in the aquifer, the age of the ground-water samples can be estimated (Busenberg and Plummer, 1992; Cook and Solomon, 1995; Plummer and Busenberg, 1999; Busenberg and Plummer, 2000).

Concentrations of dissolved gases (N_2, O_2, CO_2, Ar, and CH_4) in ground water usually are collected as part of ground-water age dating studies using CFC and SF_6 are used to estimate recharge temperatures and to help constrain recharge mechanisms. The main source of N_2, O_2, Ar, and CO_2 in ground water is air-water equilibrium during recharge (Heaton, 1981). Other potentially appreciable sources of dissolved gases in ground water include excess air or air that is mechanically entrained during recharge (N_2, O_2, Ar, CO_2), carbonate-water reactions (CO_2), and microbial activity (N_2, CO_2, CH_4) (Heaton and Vogel, 1981; Heaton and others, 1981). Air-water solubility relations (Weiss, 1970; Wilhelm and others, 1977) allow determination of recharge temperature and the amount of excess air in a ground-water sample from analysis of dissolved N_2 and Ar and by assuming the recharge elevation and the amount of excess nitrogen (N_2 produced by microbial denitrification of nitrate; Heaton and others, 1981).

Ground water from 17 wells located near the recharge area was sampled for CFCs (CFC-11, CFC-12, CFC-113), SF_6, and dissolved gases to determine the age of fresh ground water in the surficial aquifer in the study areas. The wells were purged using a submersible pump for at least three casing volumes of water, and pH, conductivity, and temperature were monitored until these parameters stabilized. The pump always was set at the top of the screened interval or near the water level in cases where the water level was beneath the top of the screened interval. The wells were revisited within 2 weeks and sampled with a sampling pump attached to refrigeration-grade copper tubing. Sampling was conducted with a stainless-steel sampling pump to eliminate CFC contamination commonly associated with pumps constructed from unsuitable materials. After pumping for 5 to 10 minutes, samples were collected in the following order: SF_6 samples, dissolved-gas samples (for selected wells), and CFC samples. Methods of collecting and analyzing CFC, SF_6, and dissolved-gas water samples are described elsewhere (Busenberg and Plummer 1992, 2000; Plummer and others 1998a, 1998b; and the USGS chlorofluorocarbon laboratory web site http://water.usgs.gov/lab/dissolved-gas/lab/ DG method.html).

Ambient-air samples also were collected once a week for 1 month from two sites (Air 1 and Air 2) in and near the Oman Mountains (figs. 2a and 2b). Air samples were collected in 500 cubic centimeter (cm^3) stainless-steel flasks equipped with inflow and outflow valves and electropolished internal surfaces. An ultrapure diaphragm-type pump connected to aluminum tubing was used to collect the air samples from approximately 3 m above land surface. The flasks were chilled and transported to the USGS chlorofluorocarbon laboratory in Reston, Virginia for analysis of CFCs and SF_6.

Dissolved-Gas Concentrations and Estimated Recharge Temperatures

Ground-water samples from 7 wells (GWP-18, GWP-235, GWP-237B, GWP-257, GWP-258, GWP-307, and GWP-352) were sampled for dissolved gases. The dominant species in these samples is N_2 followed by O_2, CO_2, and Ar, except for samples from GWP-235 that contained little O_2. Ground water from these wells likely contains minor amounts of excess air or excess N_2, and may also have undergone variable O_2 depletion.

The recharge temperature and amount of excess air in dissolved-gas samples can be determined from the N_2 and Ar concentrations and by assuming a recharge elevation and an amount of excess nitrogen. The recharge temperature was determined on the basis of Ar and N_2 ratios in dissolved gas samples collected during this study and elsewhere. The recharge temperature is calculated by extracting small aliquots of non-fractionated air from the gas content of the ground water. In the study area, recharge may occur from infiltration near the studied wells or from infiltration in the upgradient recharge areas. Recharge elevation is not critically important as the elevation difference between the sampling sites and upgradient recharge areas is less than 50 m, and the ground-water age calculations are relatively insensitive to uncertainties in recharge elevation of less than 300 m.

Without analyses of other noble gases, such as Ne and He, which help distinguish between excess air and excess nitrogen (Stute and Schlosser, 1999), it is not possible to quantify the exact amount of excess nitrogen in the dissolved-gas samples. Water samples from wells GWP-18, GWP-237B, GWP-257, GWP-258, GWP-307, and GWP-352 were assumed to have little excess nitrogen because these samples are from oxic environments. Water samples from GWP-235 were assumed to have excess nitrogen because they are anoxic and have calculated recharge temperatures from 36.7 °C to 37.1 °C. For samples from well GWP-235, the amount of excess N_2 was estimated.

The estimated recharge temperatures are presumed to be accurate within 1 °C to 2 °C, and amounts of excess air are presumed to be accurate within 1 ml/L. The calculated values of excess air range from 0 ml/L to 3.9 ml/L, and generally are within the 0 ml/L to 3.0 ml/L range typical of most ground water. The larger values of excess air were observed in water samples from GWP-235 and GWP-352 in the Al Hayer area.

CFC and SF_6 Concentrations in Ambient Air and Ground Water

Concentrations of CFC-11, CFC-12, CFC-113, and SF_6 were measured for air samples collected from sites Air 1 and Air 2 in the recharge area. The concentrations are presented as parts per trillion by volume (pptv), and plotted with the N.A. air curves for CFC-11, CFC-12, CFC-113, and SF_6 (fig. 3). The concentrations of CFC-12, CFC-113, and SF_6 in the air samples nearly are identical to N.A. air in October-November 2001. This similarity in concentrations supports the use of dating equations based on N.A. air concentrations for these compounds in the study area. In contrast, the concentration of CFC-11 in the air samples is more variable (ranging from 101.5 percent to 685.8 percent of N.A. air).

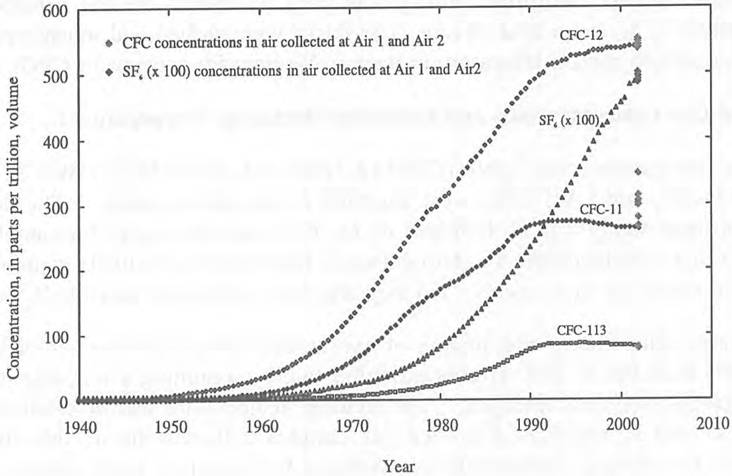

Figure 3. Concentrations of CFC-11, CFC-12, CFC-113, and SF_6 in North American air and aircollected at sites Air 1 and Air 2.

In general, five water samples for CFC analysis and two water samples for SF_6 analysis were collected from each well. For CFC samples, the results are reported for three of the last four collected samples. Well GWP-254 was sampled twice in a 10-day period and yielded similar results. Most of the 54 samples have CFC-11 and CFC-12 concentrations far below values for waters saturated with modern N.A. air. Five of the samples have CFC-11 concentrations that are 10 percent to 78 percent larger than water in solubility equilibrium with modern N.A. air, and four samples have CFC-12 concentrations that are 0.3 percent to 103 percent larger than water in solubility equilibrium with modern N.A. air. In contrast all of the 54 samples have CFC-113 concentrations that are nearly equal to or exceed those possible for equilibrium with modern N.A. air.

Possible Uncertainties Affecting Model-Recharge Dates

Four possible sources of uncertainty in model-recharge dates calculated from CFC-11, CFC-12, CFC-113, and SF_6 concentrations in ground water were identified and evaluated to the extent possible. These possible uncertainties complicate the assignment of ground-water age to the water samples. First, ground-water tracer concentrations were evaluated for possible CFC and SF_6 gas exchange between ground water and air in the well bore because there was as much as a 2-week delay between purging and sampling in some wells. Second, the source of the CFC-113 contamination recognized in all of the samples was evaluated. Model-recharge dates are considered most reliable when the analysis of all three CFC tracers yields similar results. Third, CFC concentrations of recharging water in areas having thick (greater then 10 m) unsaturated zones may not be representative of the CFC concentrations when the water infiltrated the ground after rainfall. Fourth, errors in the estimated recharge temperatures, recharge elevations, and amounts of excess air will cause errors in the calculated model-recharge dates. Because of these four possible uncertainties, the CFC and SF_6 model-recharge dates were evaluated to better understand their limitations and accuracy.

To evaluate the possibility of gas exchange in the well bore, CFC-12 and SF_6 concentrations were compared for sequential samples collected during increasing time intervals between the beginning of the pumping and the time of the sample collection (fig 4). Based on this comparison, CFC-12 and SF_6 mode-recharge dates were considered to be unreliable for the following samples: the first SF_6 samples from GWP-18 and GWP-228, both SF_6 samples from GWP-235, both SF_6 samples and the first two CFC samples from GWP-343B, and both SF_6 samples and the first CFC sample from GWP-352. All CFC samples had indications of CFC-113 contamination, however the first sample of water samples collected sequentially after a lengthy delay between purging and sampling generally had a much higher CFC-113 concentration than subsequent samples. Although the exact nature of CFC-113 contamination is unknown, materials used in the drilling and casing the wells may contribute to this contamination.

The presence of a thick (generally greater than 10 m) unsaturated zone above the surficial aquifer can cause uncertainty in CFC and SF_6 model-recharge dates. Depth to water in the study area ranges from 13 to 35 m. Where unsaturated-zone thickness exceeds 10 m, air exchange between the atmosphere and lower part of the unsaturated-zone may be slow, and the percolating rainwater may equilibrate with trapped air that has CFC and SF_6 concentrations that are representative of older air, not air concentrations when the rain fell. This trapped air will make CFC-11, CFC-12, CFC-113, and SF_6 model-recharge dates variably older than the true age of the water (Plummer and others, 2000). The magnitude of the effect depends on the diffusion coefficient and water solubility of each gas, and the water content in the unsaturated zone (Cook and Solomon, 1995). Cook and Solomon (1995) and Busenberg and Plummer (2000) have estimated that CFC-12 and SF_6 model-recharge ages can lag atmospheric ages by about 8 years in 30 m thick unsaturated zones, whereas CFC-11 model-recharge ages can lag atmospheric ages by about 12 years. The CFC-11 model-recharge dates for most water samples in the study areas are 2 years to 8 years older than the CFC-12 model-recharge dates (fig. 4), perhaps caused by percolation of recharge through the thick unsaturated zones. These data are suggestive of time-lagged model-recharge dates because of thick unsaturated zones, and may indicate that the CFC-12 and SF_6 model-recharge dates are 4 to 8 years too old and the CFC-11 model-recharge dates are 8 to 12 years too old. Because most recharge to the study area is from rainfall in the Oman Mountains where the unsaturated-zone thickness is not known, reliable conclusions about the magnitude of uncertainties in model-recharge dates caused by thick unsaturated zones are difficult to make.

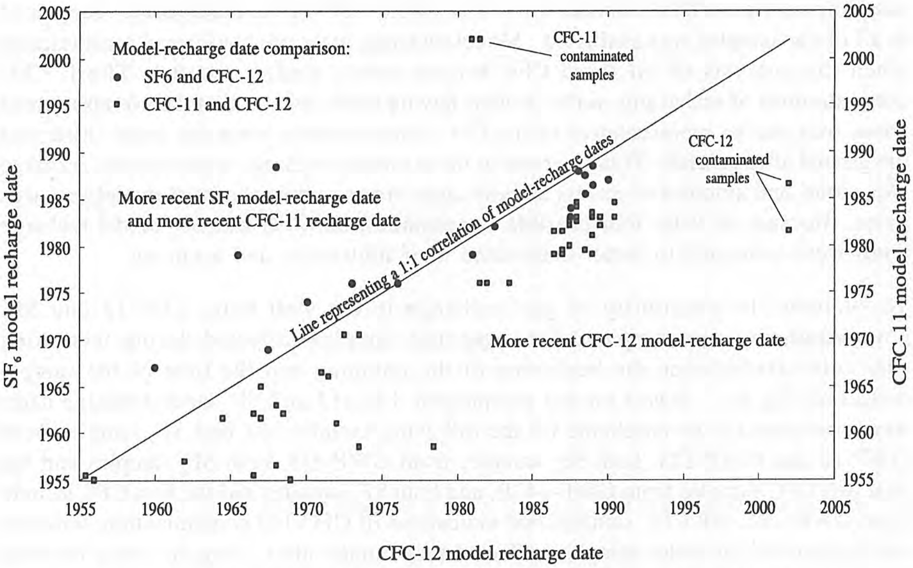

Figure 4. Comparison of CFC-12 and SF_6 estimated model-recharge dates for 17 ground-water samples from the surficial aquifer and CFC-12 and CFC-11 estimated model-recharge dates for 54 ground-water samples from the surficial aquifer.

The estimated recharge temperatures generally are accurate to ±1 °C to ±2 °C, yielding uncertainties of less than 2.5 years and less than 0.5 year for the reported CFC and SF_6 model-recharge dates, respectively. Assumed recharge elevations are well constrained to within ± 50 m given the limited topographic relief in the study areas between potential recharge sites and the sampled wells. An elevation uncertainty of ± 50 m at the estimated recharge elevations for the Al Hayer area (350 m) and the Al Jaww Plain area (450 m) produces a maximum error of less than 0.5 year in the reported CFC model-recharge dates, and has no appreciable effect on the SF_6 model-recharge dates.

Estimated Model-Recharge Dates and Ground-Water Ages

Based on the possible sources of uncertainty in the calculation of model-recharge ages, the most reliable dates were calculated from CFC-12 and SF_6 concentrations. It was not possible to determine model-recharge dates using CFC-113. Calculated model-recharge dates reported herein are dependent upon the assumptions inherent in the piston-flow model (Cook and Bohlke, 1999). The piston flow model describes the flow of water as that of a single parcel flowing along a flowline through the aquifer. The water sample will then represent tracer levels as they were during recharge. The piston flow model, which is commonly assumed in age-dating projects, produces a single age for a sample, the flow time from recharge point to sampling point.

The assigned model-recharge date (table 1) for ground water in each well was determined by averaging the most reliable CFC-12 dates and the most reliable SF_6 dates independently for each well, then averaging the average CFC-12 date and average SF_6 date for each well. The results are rounded to the nearest one-half year.

Table 1. Estimated and average model recharge date, and average ground-water age based. on CFC-12 and SF6 concentration in ground water.
[NR, estimated model recharge date considered not reliable; --, no data]

Well number (fig. 4)	Sampling date	Model-recharge date		Average model-recharge date	Average ground-water age
		CFC-12	SF_6		(years)
Ground-Water Research Project Wells - Al Hayer area					
GWP-228	15-May-2001	1976	1971	1973	28
GWP-235	27-May-2001	1968	NR	1968	33
GWP-236	14-May-2001	1967.5	1969	1968	33
GWP-237B	26-May-2001	1970	1974	1972	29
GWP-343B	6-Jun-2001	1962	NR	1962	39
GWP-352	30-May-2001	1956	NR	1956	45
GWP-353A	5-Jun-2001	1973	1976	1974	27
Ground-Water Research Project Wells - Al Jaww Plain area					
GWP-17	7-May-2001	1982.5	1982	1982	19
GWP-18	7-May-2001	1981	1973	1977	24
GWP-248A	27-Feb-2001	1989	1986.5	1988	13
GWP-254	18-Feb-2001	1988	---	1988	13
GWP-254	27-Feb-2001	1988.5	1985.5	1987	14
GWP-257	6-May-2001	1987.5	1983.5	1985	16
GWP-258	6-May-2001	1987.5	1984	1986	15
GWP-259	18-Feb-2001	1988.5	1987.5	1988	13
GWP-307	5-May-2001	1990	1987	1988	13
GWP-331	26-Feb-2001	1988	1988	1988	13
GWP-333	26-Feb-2001	1989	1988.5	1989	12

Average ground-water ages listed in table 1 are a simple computation from the average-model recharge date and the date the sample was collected. The accuracy of age dating depends on many factors and the qualified terms, apparent age, model age, or model recharge date, for the purpose of this report are hereafter called ground-water age in years. It is possible that a fraction of the water sampled may be older than the range dateable by the methods used here. An older fraction water might originate from stratified water in the surficial aquifer originating as upward flow from underlying layers, and is likely to be small.

The estimated ground-water ages for the wells sampled in the surficial aquifer in the Wadi Sinebal area near Al Hayer, range from 27 to 45 years (table 1 and fig. 2a). The sample data indicate a trend of increasing ground-water ages with depth (fig. 5), as may be expected in most hydrologic settings. Recharge along Wadi Sinebil can occur as infiltration of surface flow or as ground-water flow beneath the wadi. The dominant recharge mechanism in Wadi Sinebil (fig. 2a) may be infiltration of recharge on the wadi surface, causing consecutively younger ground-water recharge to be closer to land surface.

The estimated ground-water ages for samples collected from four wells in the surficial aquifer at Wadi Mughayrah range from 28 to 33 years (table 1 and fig. 2a). The ground-water ages show little trend with depth or with distance along the wadi. However the analysis do indicate younger ages for similar depths as compared to Wadi Sinebil (fig. 5). The small variation of ground-water ages with sampling depth and distance along Wadi Mugayrah may indicate a less stratified aquifer than at Wadi Sinebal and may indicate a combination of recharge flowing laterally away from mountain front and local recharge in the wadi.

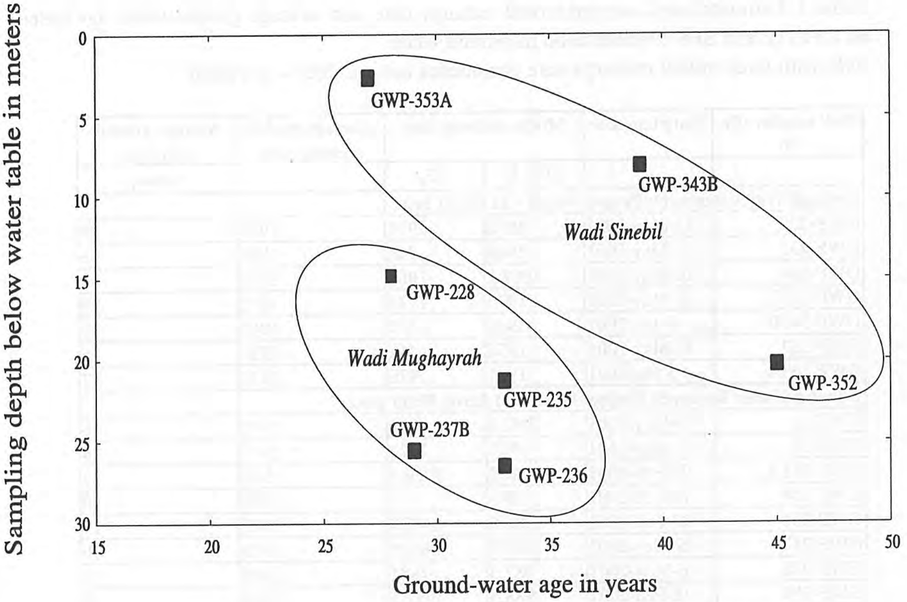

Figure 5. Relation of ground-water age and sampling depth for 7 ground-water samples from from wells in the Al Jaww Plain.

The estimated ground-water ages in the Al Jaww Plain study area range from 12 to 24 years old (table 1 and fig. 2b) and are younger than estimated ground-water ages at sampled wells in the Al Hayer area. The youngest ground water is located along a 3.3 km reach of Wadi Malaqat, where the estimated ground-water ages are tightly clustered between 12 and 14 years old. Likewise, ground-water ages along a 1.2 km reach of the southern branch of Wadi Shik near the mountain gap cluster between 16 and 17 years old. The ground-water age at GWP-17, which is from 5.2 km to 6.4 km from the mountain gap, is about 3 to 3.5 years older than in the southern branch of Wadi Shik. The oldest calculated ground-water age in the vicinity of Wadi Shik is at GWP-18 between the northern and southern branches of Wadi Shik.

The tight clustering of estimated ground-water ages along the 3.3 km reach of Wadi Malaqat and the 1.2 km reach of the southern branch of Wadi Shik indicates that recharge occurs during large but infrequent storms. The surficial aquifer can be rapidly recharged during major rainfall events when local wadi flow is substantial. For instance, a storm event (60 mm rainfall in Al Ain; probably more in the upgradient mountainous areas) on 17 April 2003 produced a water-level rise of about 7 m in GWP-258 that peaked 3 days later on 20 April 2003 (fig. 6). The water associated with the recharge was measurably cooler (about 0.2 ºC) than water in the surficial aquifer (fig. 6). Such rapid and cooler recharge probably was caused by nearby infiltration rather than infiltration from upgradient areas, however, if the recharge was only from local infiltration, ground-water levels would quickly return to pre-recharge levels. Because ground-water levels remain well above the pre-storm levels for an extended period of time (fig. 6), an appreciable part of the recharge is not local recharge, but is recharge from an upgradient area. This result is supported in that ground-water temperature returns to pre-storm levels as ground-water levels approach the higher post-storm base level. It is expected that ground-water age will increase with sampling depth below the water table. However, the samples from Wadi Malaqat and Wadi Shik were collected within 1 to 4 m of the water table and it was not possible to determine if ground-water age increases with depth beneath these wadis.

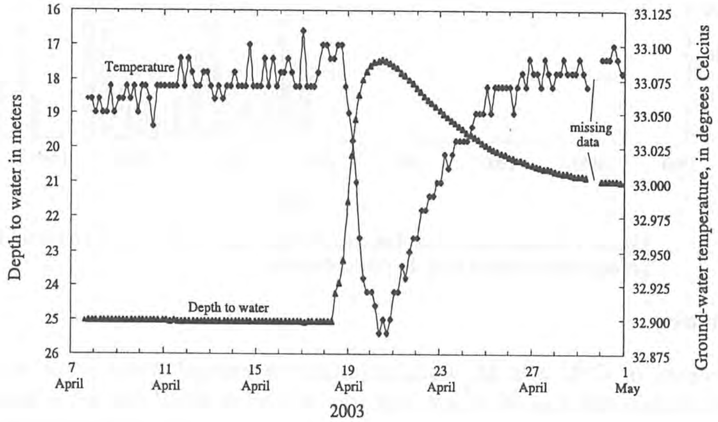

Figure 6. Depth to water and ground-water temperature in well GWP-258 in the Al Jaww Plain, 7 April 2003 to 1May 2003.

The estimated ground-water recharge ages at wells in the Al Jaww Plain generally increase with increasing distance from the Oman Mountains. Data from GWP-18 indicate that ground-water age increases in the area between wadi channels, and illustrates that recharge is larger beneath the flowing wadis than in areas not subject to flooding.

Frequency of Recharge to the Surficial Aquifer

A comparison of model-recharge dates, for the sampled wells, and annual precipitation was used to investigate the frequency of recharge in relation to the frequency of rainfall in the study areas (fig. 7). Average model-recharge dates ranged from 1956 to 1989 and included the following definable episodes of major recharge: 1956, 1962, 1968, from 1972 to 1974, 1977, 1982, and from 1985 to 1989. Post-1970 model-recharge dates determined from ground-water samples collected in the Al Hayer and Al Jaww Plain study areas indicate that recharge can occur after large rainfall events (for example, from 1972 and 1982) and after successive long-term moderate rainfall events (for example, from 1987 to 1990). It is likely that the ground-water samples collected during this study did not identify all episodes of recharge to the surficial aquifer in both study areas. The estimated model-recharge dates may be biased old or young because of uncertainties in the data, however, the episodic nature of the recharge during the past 50 years is conclusive and is expected given the highly variable annual rainfall and frequent periods of little to no rainfall in the Eastern Region of Abu Dhabi Emirate.

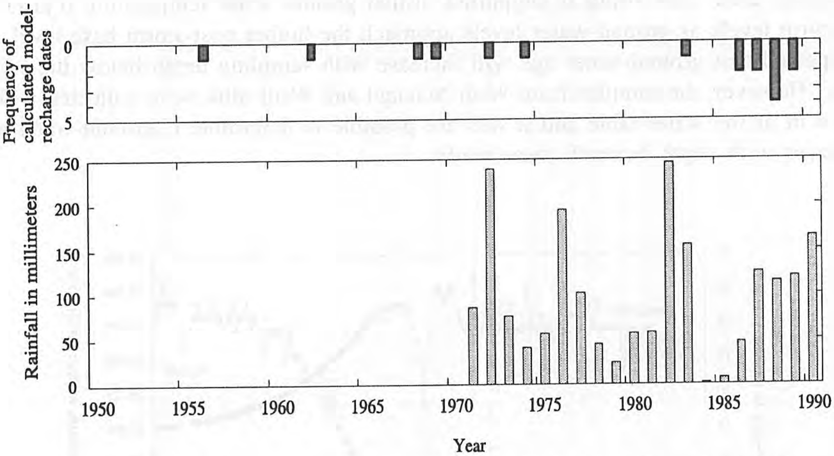

Figure 7. Annual rainfall and frequency of calculated model-recharge dates for 17 ground-water samples from the surficial aquifer.

Conclusions

Measurements of CFC and SF_6 concentrations in ground water were successfully used to constrain the age of recent recharge to the surficial aquifer underlying the eastern parts of Al Hayer and the Al Jaww Plain in eastern Abu Dhabi Emirate. CFC-12 and SF_6 appear to be the most reliable environmental tracers for dating recent recharge to the surficial aquifer. The major problems encountered during this study in applying CFC and SF_6 dating techniques are CFC-113 contamination, and potential model-recharge age uncertainty caused by the thick unsaturated zone in the study areas.

Despite the absence of local air curves for historical concentrations of CFCs and SF_6, air sampling conducted in this study indicates that N.A. air curves for concentrations of CFC-12, CFC-113, and SF_6, can be applied to date recent ground-water recharge in Abu Dhabi Emirate. More data are required to evaluate the applicability of using N.A. air curves for CFC-11 concentrations because limited results of this study show that local CFC-11 concentrations are highly variable ranging from 101.5 percent to 685.8 percent of N.A. air.

The age of ground water in the surficial aquifer in the Al Hayer and Al Jaww Plain study areas was determined to range from 12 to about 45 years. The youngest sampled ground water occurs beneath wadis that drain through mountain gaps in the Oman Mountains along the eastern edge of the Al Jaww Plain. Ground-water age may increase with distance from the mountain gaps, and in some places increase with depth beneath the wadis.

Calculated average model-recharge dates indicate episodes of major recharge occurred in 1956, 1962, 1968, from 1972 to 1974, 1977, 1982, and from 1985 to 1989. A comparison of model-recharge dates and post-1970 rainfall data indicates that recharge can occur after large rainfall events and after successive long-term moderate rainfall events. Episodic recharge is consistent with the highly variable annual rainfall and frequent periods of little to no rainfall in the Eastern Region of Abu Dhabi Emirate.

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Fog Collection in the western mountainous parts of Yemen

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FOG COLLECTION IN THE WESTERN MOUNTAINOUS PARTS OF YEMEN

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ABSTRACT

Yemen is characterized as an arid and semi-arid region which receives rainfall between 0-400 mm per year. Such rainfall is harvested and collected in cisterns that have existed in the region for generations. In the dry season (from October - March) and after the stored water is consumed, people, mainly women and children, have to travel long distances down wadis to fetch water from the nearest water source which is often not suitable for human consumption. This is the case in Hajja governorate, Republic of Yemen that heavily depends on rainwater for drinking, animal watering, domestic uses and irrigation. However, during the dry season Hajja is known as a foggy region. A fog collection study was carried out to this region in order to provide an alternative source for water supply during the dry season. This paper introduces this study on Fog Collection of the western mountainous parts of Yemen in the Hajja region. Several locations were selected and several Standard Fog Collectors (SFC @ $1m^2$) were installed. The study period was the wintry period from December 2002 to March 2003. The results showed that the fog collectors located closest to the Red Sea have produced the highest water output. In general, the best sites have produced about 4.5 liters per square meter of mesh per day over the three month wintry period. The conclusion drawn is that though this technique is cheap, simple and promising more investigation is still needed on the various parameters contributing to the fog collection, such as wind direction, relative humidity, temperature, and SFC technologies. More sites should also be studied either in Hajja or elsewhere in Yemen, such as in the eastern parts of Yemen.

Keywords: fog, water harvesting, arid, Yemen

Introduction

Water scarcity will be one of the major threats to humankind during this century. As the available water resources taken from streams, rivers and ground water will not be sufficient in most dry areas of the world to cover the needs of agriculture and urban areas. Hence, we have to reassess the value of certain traditional irrigation methods, to find out their value to ease future water scarcity [1]. Nowadays, these methods, associated with water saving techniques, modern hydrological tools and remote sensing, may supplement the other sources of water and help to secure future water supply. According to [2], and [3], Figure 1 classifies water-harvesting techniques according to the source of water used, water in the air, overland flow and groundwater.

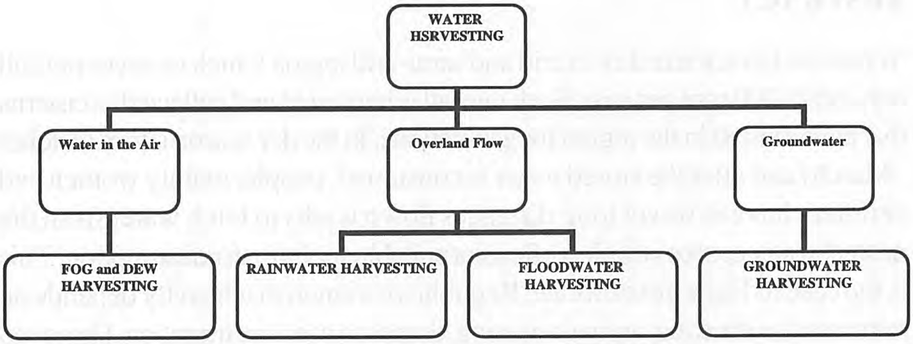

Figure 1: Water harvesting methods (Prinz, 2000)

The method of fog collection was developed in areas without permanent rivers, where people have to rely on rainfall, dew and fog. This innovative technology is based on the fact that water can be collected from fogs under favorable climatic conditions to provide water for small rural communities in arid and semi-arid regions. This non-classical water harvesting method is simple and can be applied without large investments. It can also be maintained and managed by the users and hence offers good prospects for future development. The challenge is to identify suitable communities and environmental conditions, ensuring that the system meets user demand sustainability, and incorporates a system that is efficient to collect water for regional agricultural purposes.

The modern area of fog collection began in 1987 with the construction of a pilot project of 50 fog collectors at El Tofo, Chile [4]. In 1992, the water from these collectors was taken to the village of Chungungo. In the immediate following years, the number of fog collectors on the mountains was increased to 100 and the average fog water production was 15000 liters per day through the year. Since that time the number of fog collectors has varied somewhat depending on need and circumstances. As a result of these projects, other fog collection projects have been initiated in Chile and in countries such as Peru, Ecuador, South Africa and the Canary Island of Spain [5]. In addition, there have been evaluations in a number of countries, such as Mexico and the Sultanate of Oman.

Objectives of the Study

This study aims to describe the fog harvesting technique applicability in Yemen, in addition to obtaining sufficient data for making a reliable estimate of the daily yield through out the year. This was based on real experimental applications in nineteen different sites in the Hajja governorate, northwest of the capital city of Sana'a, Yemen Republic and inland from the Red Sea. It is also important to deduce any seasonality and the best placement and orientation of the large collectors for greatest yield. This information is vital to the design process to ensure the best performance at an affordable cost.

Study Area

Hajja is one of the governorates of the Republic of Yemen. It is a mountainous region located in the west of the country with altitude ranging from 1650m to 2480m above sea level (Figure 2). Many people in Hajja depend heavily on rainwater for drinking, animal watering, domestic uses and irrigation. In Hajja rain annually falls between March – May and July – September and during the dry season Hajja is known as a foggy region; and hence it, was chosen for this pilot study.

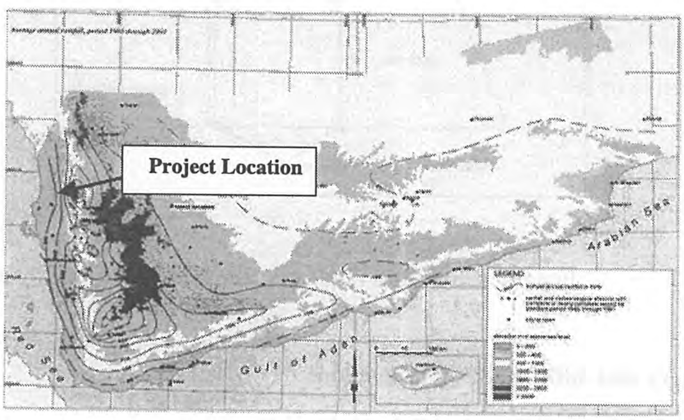

Figure 2: Location of the Pilot study area in Yemen

Standard Fog Collectors

Standard Fog Collectors (SFCs) are defined by Schemenauer and Creceda, 1994. The collectors are simple, flat; rectangular nets (mesh) of nylon supported by a post at either end or set perpendicular to the direction of the prevailing wind. The one used in the pilot-scale project in the Hajjah region of Yemen consisted of a one square meter panel of mesh held 2m above the ground by a supporting structure (Figure 3). It is constructed with locally available materials and local workmanship, except the mesh, which was imported from England in order to guarantee standardization with projects in other countries.

As water collects on the net, the droplets join to form larger drops that fall under the influence of gravity into a trough or gutter at the bottom of the panel, from which it is conveyed to a storage tank or cistern. The collector itself is completely passive, and the water is conveyed to the storage system by gravity. If site topography permits, the stored water can also be conveyed by gravity to the point of use. The storage and distribution system usually consists of a plastic channel or PVC pipe approximately 110 mm in diameter, which can be connected to a 20 to 25 mm diameter water hose for conveyance to the storage site/point of use which is usually a closed concrete cistern.

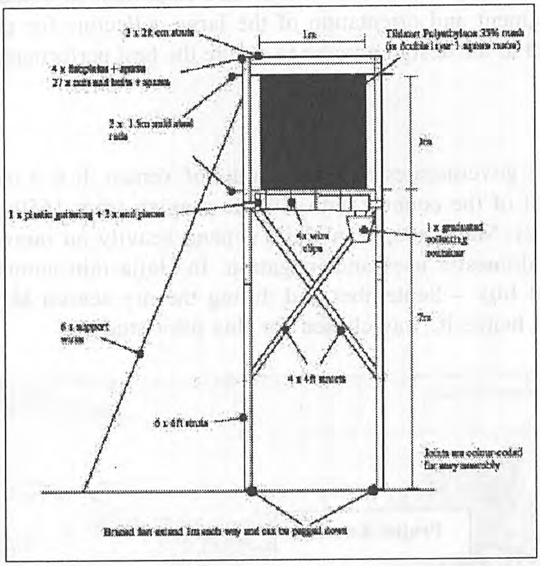

Figure 3: Standard Fog Collector (SFC) in the study area

Parameters that Influence Fog Collections

1. Global wind patterns

Conditions for fog water harvesting are best where there are persistent winds from one direction to transport low-level cloud and fog. Figure 4 shows the west-east cross section of an idealized case for a Tihama coastal plain, such as Yemen, and Saudi Arabia. This is a very simplistic explanation; fog in these desert areas can be caused by much more complex atmospheric and oceanic interactions that are not properly understood. In the western part of Yemen, this coastal fog gives only moderate yield and has lower wind speeds than in the inland and eastern regions (e.g. Al-Mahra district).

2. Mountain range

The topographic relief must intercept the cloud. With low-level coastal fog, this can be isolated hills or dunes. For higher cloud, larger mountains are needed. In this latter case, the clouds can be pre-existing or orographically induced.

3. Distance to the coastline

Marine clouds and fog decks generally dissipate further inland due to evaporation. It is often therefore desirable to have collectors located within 5km of the coast and usually not more than 25km. This distance must be balanced against topography in relation to the cloud deck. Observations and experiments are needed to determine the optimum location. In high elevation areas where clouds are intercepted or induced by the topography, the distance to the coast is irrelevant.

4. Rainfall seasonality

Fog harvesting is not restricted to hyper-arid areas. There is potential application in highland tropical areas. The rainfall in these areas, though generally very high, is often very seasonal and there may be application for fog collection as a dry season water supply. The rainfall in Yemen depends on two main mechanisms, the Red Sea Convergence and the Monsoonal Inter tropical Convergence Zone. The former influence is most noticeable in the west of the country; this is active from March to May and to some extent in autumn, while the latter reaches the country in July-September, moving north and then south again so that its influence lasts longer in the south. Seaward exposed escarpments such as the western and southern slopes receive more rainfall than the zones facing the interior. The average temperature decreases more or less linearly with the latitude.

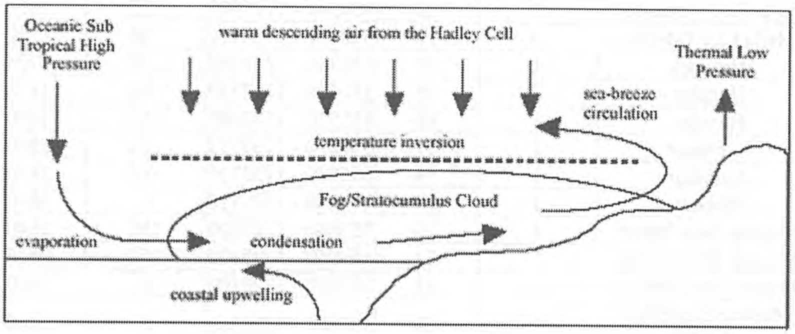

Figure 4: West Coast Advection Fog

Field Work and Measurements

Planning for the fieldwork began in November 2002 and subsequently 26 small Standard Fog Collectors (SFCs) were constructed. In early January, 2003, nineteen different sites were chosen and the 26 small Standard Fog Collectors (SFCs) were installed in the mountains of Yemen near Hajja, north-west of the capital city of Sana'a and inland from the Red Sea. Table 1 shows the locations, orientations and the elevations of the SFCs in the study area.

The SFCs were preferentially sited on ridges and saddle points in positions where experience has shown that there will be strong enough winds to push the fog through the mesh of the collectors. The SFCs are located facing south and west directions depending on the local topography, which is because the prevailing winds during the months of December, January, February and March are from the south and sometimes west [6].

The harvested fog water was measured on a daily basis. Measurements lasted from 1 January to 31 March 2003. These are the dry months in winter when rainfall is virtually non-existent and the need for water is very high.

Table 1: Detailed Table of Locations SFCs in the study area

Area name	Site Number	SFC Number	Location UTM)	Orientation	Elevation
Schiraqi	1	1	352061 - 1729727	180	2260
Schiraqi	1	2	352061 - 1729727	270	2260
Schiraqi	2	3	352530 - 1730131	170	2450
Schiraqi	2	4	352530 - 1730131	270	2450
Schiraqi	3	5	352662 - 1730058	240	2450
Schiraqi	4	6	352887 - 1730132	180	2450
Schiraqi	5	7	352312 - 1729695	190	2300
Mabyan	1	8	346743 - 1739771	230	2020
Mabyan	2	9	346622 - 1739871	215	2030
Mabyan	3	13	347000 - 1739300	270	2000
Mabyan	4	10	347416 - 1737470	200	1650
Hajja City (Antenna)	1	11	350366 - 1735330	225	1820
Hajja City (MOA)	2	12	350114 - 1734950	180	1750
Humlan	1	14	351331 - 1733100	230	1775
Humlan	2	16	351420 - 1732770	270	1835
Humlan	3	15	351520 - 1732080	250	1890
Aschmur	1	17	366230 - 1735710	270	2840
Aschmur	1	18	366230 - 1735710	180	2840
Aschmur	1	19	366230 - 1735710	0	2840
Maswar Bait Sheim	1	20	357050 - 1728100	180	2640
Maswar Bait Sheim	1	21	357050 - 1728100	250	2640
Maswar Bait Sheim	2	22	357220 - 1728100	0	2660
Maswar Bait Saad Salah	3	23	355000 - 1727600	0	2440
Maswar Bait Saad Salah	3	24	355000 - 1727600	270	2440
Maswar Bait Saad Salah	4	25	355000 - 1727350	180	2485
Maswar Bait Saad Salah	4	26	355000 - 1727350	270	2485

Results and Discussion

The results from data records and measurements during the study period from1 January 2003 to 1 March 2003 shows that, the fog water collection rate is not acceptable in most collectors according to [4], while the collection rates in the collectors numbers 9, 8, 13, 24, 26 and 23 are moderate with an average around 1 liter per day (Figure 5). Based on the data collected, the fog collection sites in Mabian (SFC 9) showed that the fog collectors have produced the highest water output in the Mabian district, which is of all the different investigated sites, the closest to the Red Sea. The data trend also shows that mid-January to the end of February is a dry period with lower water production while during the month of March the water production rate is excellent. The data also shows that the collectors on the highest sites did not produce a significant amount of water. It is worth noting that as the climate may vary from a year to another, defining the daily, weekly, monthly and annual variations is important in order to determine both the water availability and the water storage requirements.

Figure 6 shows the variation of fog collection with wind-direction. It is obvious that the west winds are the most productive. This humid air comes from the Red Sea and Mabian is the first mountain range encountered on the way inland. Data sites 9 and 8 had the best collection rates, were well exposed to winds coming from the west up a major wadi. Site 13 was in the same area but had lower collection rates as the exposure to the west winds was not as good as the others. However, in light of the observations that collection rates were higher with southwest winds, it would be valuable to examine several new sites to the north of the city which may be proved to be productive.

Figure 7 shows the variation of fog water collection with different wind speeds. In the evaluated area in the Hajja governorate it shows that the fog is present with low wind speeds. Almost 50% of the water collection occurred when the wind speed was around 2 of the Beaufort wind speed.

The variation of the fog water collection with elevation in Figure 8 shows good collection amounts between elevations of approximately 2000 and 2500m above sea level. The collection rates for these sites are from 1.12 to 4.5 liters per square meter of mesh per day in the Mabian and Maswar districts. This range of altitudes is a good starting point to continue testing fog collection in Yemen, especially since many villages are located at these altitudes. In general, all the ridges and mountain chains located from the north to the south above 2000 m would be potentially good productive sites and should be evaluated.

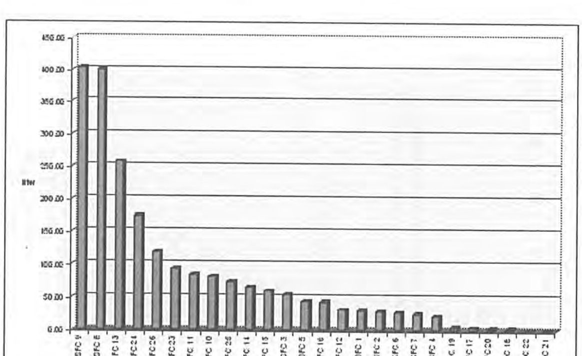

Figure 5: Total fog water collection in the project area for the period (1 Jan. - 1 March)

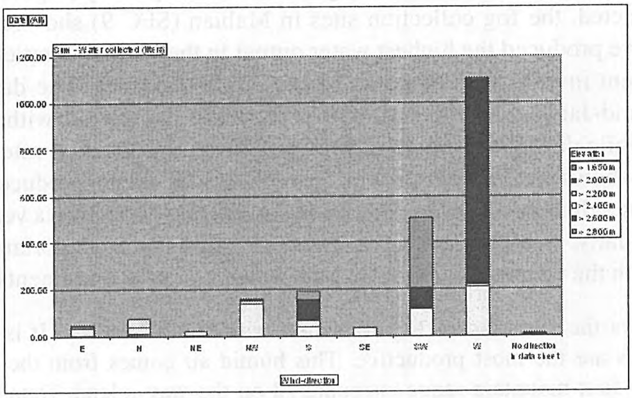

Figure 6: Variation of the fog water collection with wind direction

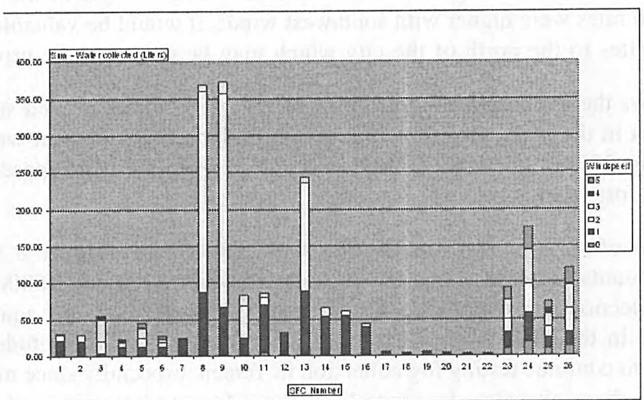

Figure 7 Variation of the fog water collection with wind speed

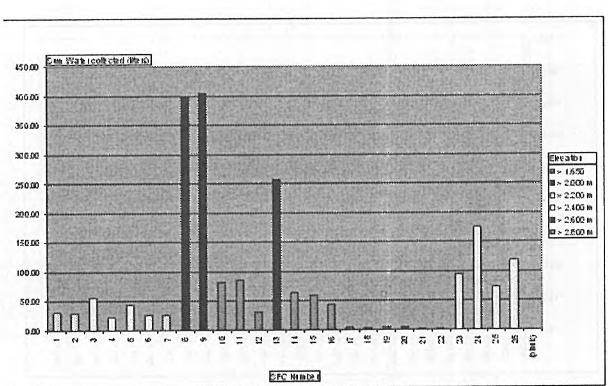

Figure 8: Variation of fog water collection with altitude in the project area

Conclusion and Recommendations

Fogwater harvesting is an appropriate technology solution that can be built, managed and maintained by rural communities, although selected communities are likely to require external resources and skills to identify suitable harvesting sites.

The most important recommendations of this study are:

- More investigation is needed on the various parameters contributing to fog collection, such as wind direction, relative humidity, temperature, distance to the coastline and SFC technologies,
- More sites should be studied either in Hajja or elsewhere in Yemen such as in the eastern parts of Yemen.
- Operational requirements should be considered which include measurement of the volume collected and recording of meteorological data, either manually or by automatic weather station, since changes in weather conditions may change the operational design of the harvesters.
- More efficient meshes are needed to increase the l/m^2 yield to keep costs and space requirements down.
- Greater awareness of fog-harvesting technology is needed in the rural water supply sector and good understanding of its opportunities and constraints.
- More research is needed on the dynamics and chemistry of fog in order to optimize quality and yield.
- Expansion assessment needs further investigation.
- Sufficient attention must be given to social and economic aspects.

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An Investigation of the Alluvial Aquifer of Wadi Hawasina Catchment and the Effect of the Dam on Groundwater Recharge and Quality, Oman

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AN INVESTIGATION OF THE ALLUVIAL AQUIFER OF WADI HAWASINA CATCHMENT AND THE EFFECT OF THE DAM ON GROUNDWATER RECHARGE AND QUALITY, OMAN.

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ABSTRACT:

The study area is Wadi Hawasina located in north Batinah where groundwater is the primary natural water resource available. Wadi Hawasina has a catchment area of about 982 km^2. There is one recharge dam built in January 1995 in the study area. The rapid and significant development in the study area has resulted in an increase in water demand. Excessive pumping has resulted in a decline of groundwater levels which lead to migration of saline/fresh groundwater interface inland. This has led to an increase in groundwater pollution by salinization, both in the immediate vicinity of the coastal wells and further inland, causing more farmlands near the coast to be lost. The present groundwater quality was evaluated and compared with the groundwater quality before the dam construction and impoundment. Two geophysical profiles were conducted using the Time Domain Electromagnetic Method (TDEM) to determine the interface between fresh water and saline water in the aquifer. The study shows that dam construction in the study area has resulted in an increase in recharge of groundwater into the alluvial aquifer in the vicinity of the dam. The groundwater quality in the vicinity of the dam has slightly improved. Near the coast groundwater quality has deteriorated because of the excessive pumping. Saline water intrusion has been found to exist over a distance of about 4 km from the coast line. Also, saline/fresh water boundary migration downgradient of the dam in the main wadi channel has not advanced inland as much as in surrounding areas.

1. INTRODUCTION

1.1 GENERAL

The Sultanate of Oman is located southeast of the Arabian Peninsula between latitudes 16° 40' and 26° 20' North and longitudes 51° 50' and 59° 40' East with a total area of about 314,000 km^2 (Figure 1). Oman has semi-arid climate with average annual rainfall of about 100 mm. Average rainfall in the coastal areas is approximately 75 mm per year but because of the orographic effect it reaches approximately 200 mm per year in mountainous areas. From June through August the monsoon rainfall occurs along the southern coast but it is of low intensity, being more like a mist. The Batinah region is considered to be the most densely inhabited area in Oman after the capital Muscat. Batinah region form about 50% of the farm land irrigated in Oman. Agriculture is mainly concentrated near the coast where groundwater levels are close to the surface and soils are more fertile. Dug wells and boreholes are used to irrigate these areas. Excessive abstraction along the Batinah coast has caused ingress of seawater with consequent deterioration in groundwater quality.

1.2 STUDY AREA

The study area is Wadi Hawasina Catchment (Figure 1), which is located in northern Batinah where groundwater is the primary source of natural water. The study area is bounded by Wadi Mashin to the east and Wadi Shafan to the west. Wadi Hawasina drains northward from the Jabal al Hajir al Gharbi and has a catchment area of about 982 km^2. Annual rainfall varies from 86 mm/year near the coast to about 147 mm/year in the mountains. On the coast, dug wells and boreholes are used extensively for agriculture purposes. Groundwater quality in the study area has deteriorated during the last few decades due to irrigation water return and the encroachment of saline water into the coastal aquifer. Wadi Hawasina dam was built in January 1995 and is located 8 km west of Al Khabourah town. The dam is provided with 1,135 m long spillway of concrete weir. The dam is a zoned type earth fill dam with dimensions of 6.8 m in height and crest length of 5.9 km. The capacity of the reservoir is 3.7 million cubic meter [1].

1.3 LITERATURE REVIEW

The Batinah area been studied by different government agencies and international consultants during the 20 year period of water resources investigation in Oman. International Land Development Consultants, 1975 [2], Sir Alexander Gibb and Partners, 1976 [3], Stanger Gordon 1986 [4], MacDonald and Partners limited 1992 [5], Ministry of Water Resources (MWR) 1995, [6], MWR, 1996 [7], and Young et al. 1998 [8], conducted hydrological and hydrogeological surveys on different areas along the Batinah plain. Salinity condition and water resources assessment of Wadi Hawasina formed an important part of these studies.

1.4 OBJECTIVES

The main objectives of this study are to assess the effect of Wadi Hawasina dam on groundwater recharge and quality and to investigate the seawater intrusion in the study area due to the effect of pumping for irrigation.

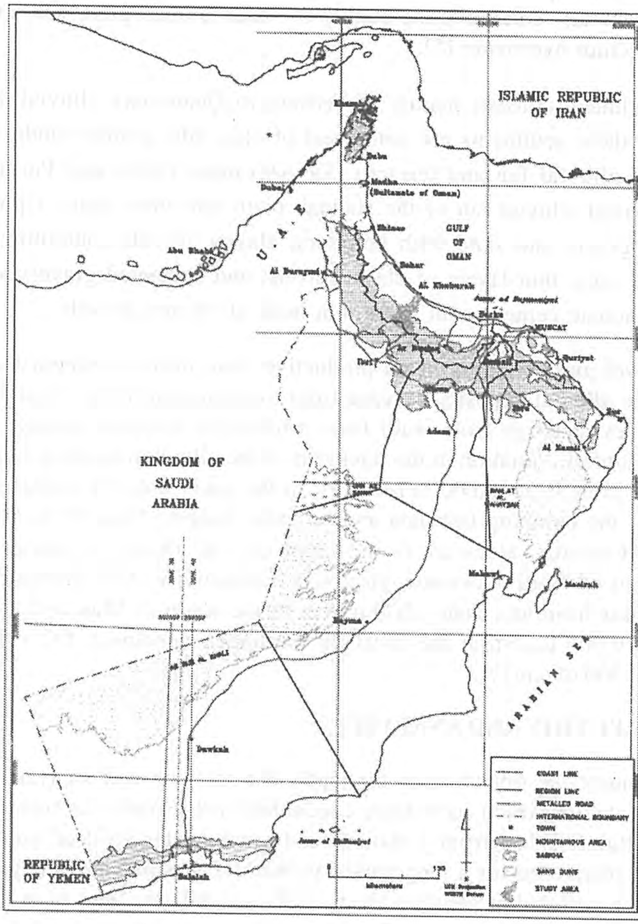


Figure 1: Map showing the location of the study area, Oman.

2. GEOLOGY AND HYDROGEOLOGY

The geology of Wadi Hawasina Catchment is shown in Figure 2. The main lithological units in the study area are Tertiary to Quaternary alluvium, Tertiary limestone, Samail Nappe and Hawasina Nappe. The catchment is divided into two subdivisions, an upper mountain region and lower sand and gravel plain. Hawasina Nappe and Samail Nappe are the major rock outcrops and dominate the upper catchment. Hawasina Nappe outcrops extensively in the study area and is composed mainly of limestone and cherts but also including sandstone, andesite and basalt. Hawasina Nappe is basically impermeable and is not a good aquifer. The Samail Nappe Ophiolite is composed of primary Ophiolite suite crustal and mantle sequences. The crustal sequence consists of gabbroic and basaltic units which have been affected by tectonic movement. Mantle sequence consists of tectonized harzburgite, peridotite and dunite. In the Batinah area, Ophiolite (peredotites, gabbro, etc.) are known to contain springs but these are generally small and the quality of water is often poor, very alkaline and saturated in calcium hydroxide [5].

The lower catchment consists mainly of Tertiary to Quaternary alluvial deposits. In the study area these sediments are composed of clay, silt, aeolian sands, and recent and sub-recent alluvial fan and terraces. Sir Alexander Gibbs and Partners (1976) divided the coastal alluvial fan of the Batinah plain into three units: Upper gravels-beds of clean gravel and sand with boulders; clayey gravels-containing clays and marls but with some thin layers of clean gravels; and cemented gravels-white clays, marls, and carbonate cement with some thin beds of cleaner gravels.

The upper gravel unit forms the most productive zone in the Northern Batinah. The thickness of the alluvial deposits increase from the mountain front towards the coast. Alluvial receives recharge from wadi flow infiltration, bedrock seepage and direct infiltration of rainfall. Variation in the thickness of the alluvium result in transmissivity values ranging from 10 to10,000 m^2/day [9]. In the study area the transmissivity was estimated from the pumping test data and its value ranging from 36 to 5600 m^2/day. Hydraulic conductivity values are in the range of 1 to about 243 m/day [5]. In the lower catchment of Wadi Hawasina, electrical conductivity (EC) gradually increases towards the coast from less than 1,000 µS/cm in the south of Muscat-Sohar highway to more than 16,000 µS/cm at the coast. In the upper catchment, EC values ranged from 1,100 to 2,300 µS/cm [7].

3 DATA COLLECTION AND ANALYSIS

In order to achieve the objective of the study, the revision and analysis of the data from previous studies which have been conducted in the Wadi Hawasina Catchment is performed. Rainfall data from 2 stations and groundwater level of some boreholes that have been monitored for a long period in Wadi Hawasina were analyzed in order to determine the correlation between the rainfall, groundwater elevation and the dam implementation. In addition 36 groundwater samples were collected and 2 geophysical profiles were conducted during this study. Water quality studies usually analyze for the eight major ions of Na^+, Ca^{2+}, K^+, Mg^{2+}, SO_4^{2-}, Cl^-, HCO_3^-, and CO_3^{2-}, along with iron and nitrate [10]. In addition to these inorganic analyses, some of the groundwater samples were analyzed for trace metals. The results of the current round of samples and the available 1994 chemical analyses were plotted on Stiff diagrams to aid in visualizing temporal and spatial changes of water chemistry within and between sites. Stiff patterns are graphical presentations of the concentrations of anions and cations, expressed in milliequivalents/liter. The comparison between the 1994 groundwater samples with the newly collected data was made in order to detect the change in groundwater chemistry and to assess the effect of the dam on groundwater recharge and quality. The Time Domain Electromagnetic Method (TDEM) was used to conduct the two geophysical profiles in the study area.

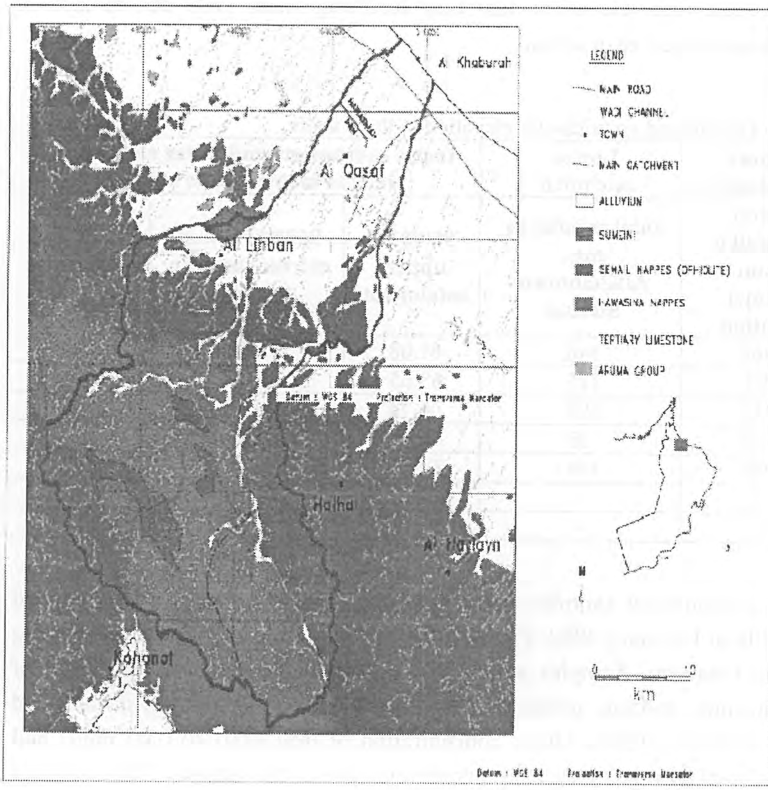


Figure 2: Geological map of Wadi Hawasina, Oman.

4 DISCUSSION

Generally, an increase in precipitation and a prolonged time for recharging the groundwater by a physical barrier leads to an increase in groundwater elevation [10]. The annual rainfall has peaked in 1995 and 1997. This increase in annual rainfall input has resulted in an increase in water level elevation in both upper and lower catchments. While there is a correlation between rainfall and groundwater elevation in both catchments, the effect of dam impoundments is quite apparent in the immediate area near the dam and downgradient from the dam. Table 1 presents the annual rainfall in the upper and lower catchments and shows the monthly average water elevation in three wells located above, below, and in the vicinity of the dam. While the increase of rainfall led to an increase in groundwater elevation by approximately 3 to 6 m in the areas lower and far above the dam, an increase of groundwater elevation by approximately 14 m is observed in the vicinity of the dam. An increase of approximately

8 m in groundwater elevation is due to dam water impoundment. This is due to decreasing wadi run off flow to the sea and prolonging the time for infiltration to the subsurface. Groundwater elevation has been declining since 1999 due to lack of rainfall and groundwater abstraction.

Table 1: Annual rainfall and groundwater elevation in three wells

	Upper Catchment	**Lower catchment**	**Yearly average ground water elevation in wells in meters above sea level**		
Year	**Total rainfall in mm Majzi Station**	**Total rainfall in mm AlKhaburah Station**	**960/022 upper catchment**	**960/025 lower catchment near the dam**	**960/017 lower catchment near the coast**
1995	268	246	61.08	7.54	0.33
1996	97	125	63.65	13.05	1.25
1997	362	286	66.24	14.68	2.16
1998	122	63	66.59	21.41	2.87
1999	90	154	64.30	19.47	2.78
2000	-	-	62.21	13.63	1.87
2001	-	-	61.20	6.54	1.20

A total of 36 groundwater samples were collected from monitoring boreholes and farmer dug wells in February 2002. Figure 3 shows the monitoring boreholes and dug wells sampling locations. Samples were analyzed for the inorganic constituents of calcium, magnesium, sodium, potassium, bicarbonate, chloride, sulfate, nitrate, and Total Dissolved Solids (TDS). Minor concentration of iron (0.01 to 0.02 mg/l) and chromium (0.02 to 0.04 mg/l) were also reported in some of the samples. The results of the analyses were examined by graphical means in order to evaluate temporal and spatial changes in water quality. Current water analysis results along with the results from the 1994 sampling round are presented in Table 2. The results of selected wells were also plotted on Stiff diagrams in order to aid in the visualization of differences in water chemistry across Wadi Hawasina near the dam and close to the coast (Figure 4). Groundwater quality in wells near the dam (wells: 220/608 and 220/775) remained the same or slightly improved between 1994 and 2002. However, groundwater quality has deteriorated in wells north of the main road and approximately 2 km south of the coast line (wells: 221/092, 487, and 519). Maintaining or improving groundwater quality in the vicinity of the dam can be attributed to the increase in groundwater recharge due to dam implementation. The deterioration of groundwater quality in wells closer to the coast is the result of seawater intrusion due to excessive pumping of water for irrigation purposes in the area. Two geophysical profiles were also executed in the study area. One TDEM profile was executed in the west side of the study area in order to determine the extent of saline intrusion and is presented as a geo-electric section in Figure 5. The other TDEM profile was executed in the east side of the study area in order to determine the extent of saline intrusion with its variation according to depth and to compare the results with the western profile this is presented as a geo-electric section in Figure 6. This profile shows that the saline water intrusion appears to have been progressed more inland (>5 km) than the western side (4 km). There is a striking similarity between the TDS map (Figure 3) and the TDEM profiles. The TDS map shows that the saline intrusions in the western side is not as advanced as in the eastern side, and is confirmed by the TDEM profiles. TDEM geophysical surveys have not only mapped the saline water intrusion but also predicted depth of saline water intrusion.

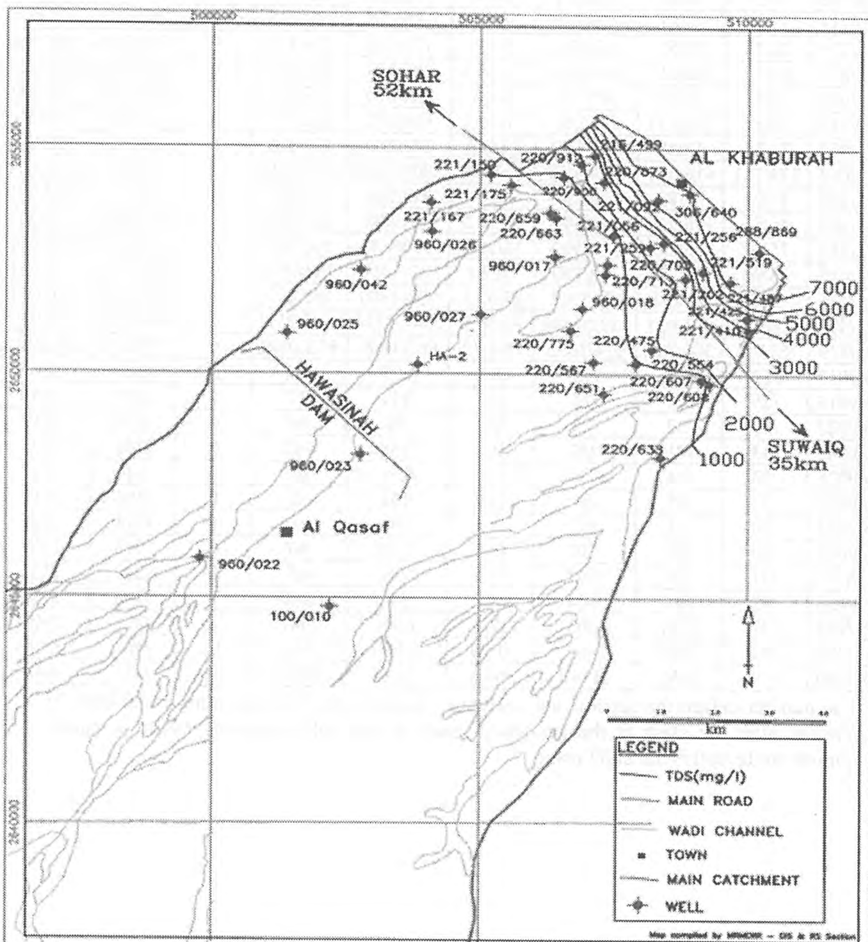
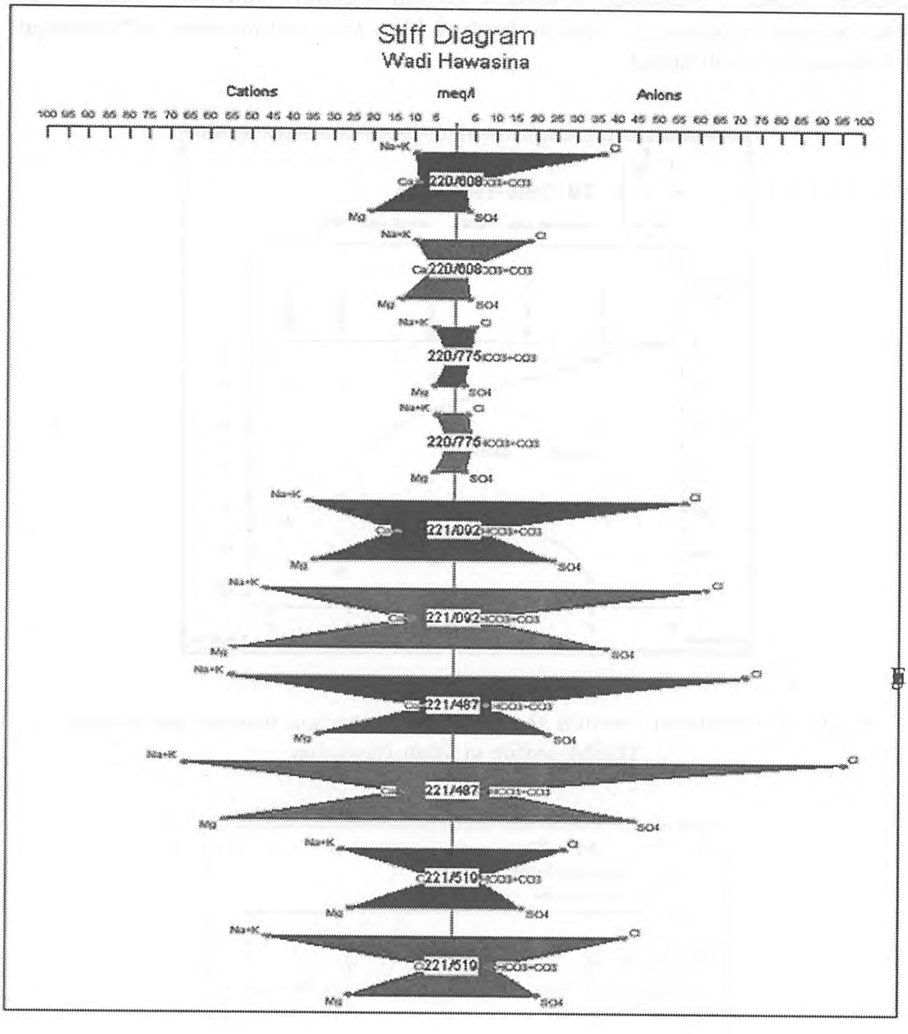


Figure 3: Sampling well locations and TDS in Wadi Hawasina (2002), Oman

Table 2: Groundwater analyses results of the 1994 and 2002 sampling events

Well No.	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	Cl (mg/l)	SO4 (mg/l)	Co3 (mg/l)	Hco3 (mg/l)	TDS (mg/l)
220/475	33/68*	86/208	192/274	9/7.7	344/821	239/348	0	261/270	1043/1915
220/567	24/26	57/57	86/80	5/ 3.3	127/129	90/69	0	266/265	529/523
220/607	30/38	62/67	108/112	3/ 4.6	217/254	118/83	0	178/180	672/705
220/608	179/109	251/160	215/205	11/ 6.4	1288/649	156/166	0	133/144	2205/1434
220/638	34/35	75/69	102/98	5/3.2	186/189	122/114	0	229/205	680/642
220/651	31/29	64/59	112/97	6/3.8	217/155	122/137	0	235/256	680/630
220/659	23/32	73/73	62/99	6/3.8	193/186	84/116	0	218/298	559/680
220/663	22/30	73/64	89/86	8/3.9	117/169	83/110	0	252/258	585/606
220/703	17/27	40/68	102/131	6/4.4	118/150	88/173	0	243/288	502/711
220/713	27/23	74/61	125/114	9/4.4	219/117	141/133	0	269/313	775/625
220/775	28/28	59/57	106/98	5/3.7	170/116	104/116	0	230/262	605/568
220/873	63/79	208/217	455/459	21/18.3	935/873	330/371	0	480/499	2253/2281
220/900	22/44	56/92	185/120	9/4.8	204/270	127/222	0	329/260	798/898
220/912	53/57	116/133	575/350	21/10.2	884/632	463/231	0	312/361	2279/1606
221/056	21/34	61/83	220/150	11/6.2	247/280	184/121	0	337/363	922/880
221/092	279/211	416/654	810/1050	26/20.8	2009/2200	1166/1800	0	330/304	4872/6118
221/150	31/27	87/83	170/139	6/4	312/200	155/80	0	314/333	883/720
221/202	48/84	148/210	341/347	20/10.5	553/800	262/500	0	440/269	1614/2120
221/256	75/62	218/187	518/562	13/10.3	950/900	560/586	0	386/524	2530/2606
221/410	53/96	133/224	378/700	12/9.1	717/1661	231/294	0	367/319	1712/3167
221/425	3/82	51/231	479/1321	27/37.7	520/1800	280/697	0	476/698	1601/4564
221/487	126/244	401/681	1232/1490	32/36.9	2545/3398	1127/2121	0	490/461	5658/8234
221/519	63/75	304/307	614/1033	18/14.3	967/1500	813/1000	0	350/583	2966/4251
960/017	/27	/39	/93	/3.1	/129	/87	0	/217	/500
960/018	/25	/41	/78	/3.3	/114	/73	0	/207	/451
960/027	/23	/33	/75	/2.9	/98	/60	0	/209	/413
960/042	/33	/41	/107	/3.6	/148	/102	0	/246	/573
960/026	/33	/44	/114	/3.6	/154	/103	0	/246	/588
960/025	/32	/45	/84	/3.1	/144	/88	0	/196	/510
960/023	/30	/41	/87	/3.5	/96	/84	0	/216	/464
960/022	/36	/40	/103	/3.5	/149	/97	0	/218	/552
HA-2	/31	/36	/107	/3.5	/148	/87	0	/209	/531
220/630	/47	/96	/124	/4.2	/300	/200	0	/206	/925
221/259	/79	/191	/501	/9.3	/989	/547	8	/291	/2494
216/499	/92	/235	/402	/15.3	/1000	/334	13	/481	/2349
306/640	/172	/650	/1140	/64.6	/2200	/2000	0	/471	/6482

- The number before the slash is the analytical result of the 1994 sampling event and the number after the slash is the analytical result of the 2002 sampling event. A single number in the cell is the 2002 result.



4: Stiff diagram showing groundwater chemistry for 1994 and 2002. Polygons for the same well are staked so that 1994 is on top of 2002 polygon.

Electrical conductivity in the study area is gradually increasing towards the coast from less than 1000 μS/cm in the south of the highway to more than 12,000 μS/cm near the coast, this level is in agreement with the decreasing resistivity trend towards the coast line. TDEM results point out that the saline water intrusion in the study area has advanced inland to a distance of about 4 km and is dipping about 45° towards land. Near the coast it appears at a shallow depth of 10 to 15 m and increases to 90 m depth at a distance of 3 km inland.

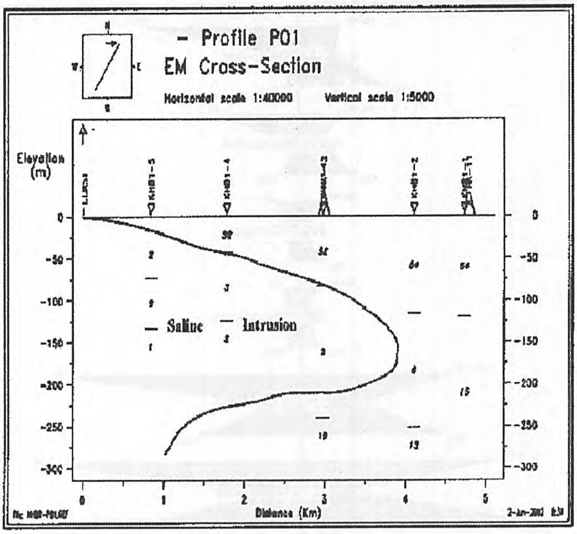


Figure 5: Geoelectric section showing saline intrusion beneath the western TDEM profile in Wadi Hawasina

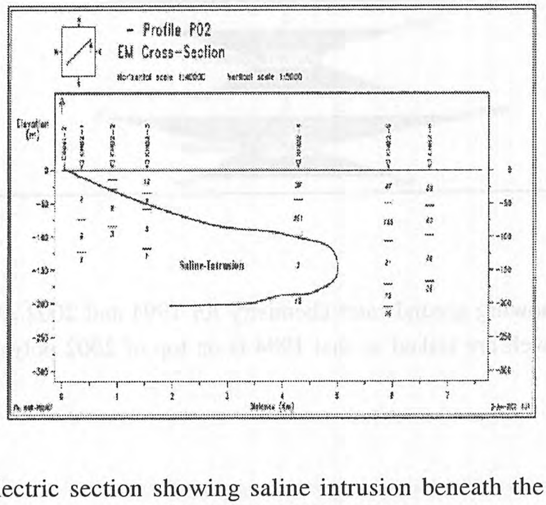


Figure 6: Geoelectric section showing saline intrusion beneath the eastern TDEM profile in Wadi Hawasina.

5 CONCLUSION

The installation of the dam in Wadi Hawasina in 1995 has lead to an increase in groundwater recharge into the alluvial aquifer in the vicinity of the dam. Groundwater quality has deteriorated in the alluvial aquifer near the coast due to seawater intrusion because the over draft of water for irrigation. The geophysical survey (TDEM) indicates the existence of saline water intrusion over a distance of about 4 km from the coast line. The Wadi Hawasina dam may on the long term stop seawater intrusion and improve groundwater quality in the coastal region in the lower catchment of Wadi Hawasina.

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Rainfall-runoff modelling in the arid areas

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RAINFALL-RUNOFF MODELLING IN ARID AREAS

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ABSTRACT

Rainfall-runoff modelling is a very important tool in hydrology. It can help in water resources assessment and management, in the design of flood protection and in flood forecasting. It can be considered as a key component for studying the dynamic aspects of hydrological processes in arid areas and can aid in assessing the likely impact of future hydrological changes. It also can be used as a tool to estimate missing data. However, the hydrological characteristics in arid areas are very different from those of wet areas. The rainfall and runoff in arid areas are generally sparse but intense with high variations both spatially and temporally, and runoff can be strongly affected by channel transmission losses. Evapotranspiration is very large, and in addition, the vegetation cover is sparse and varies with time. Rainfall-runoff modelling in arid areas needs special attention to consider these characteristics, bearing in mind that most of the current models are developed for wet areas in which the special characteristics of arid areas are not well considered or represented. However, the hydrological network cover in most arid areas is sparse with short periods of record except in a few locations. The quality of the hydrological data is also questionable. As much of the world's arid areas are in developing countries, resources are limited, which is an obstacle in improving the networks or developing new models that concentrate on arid area features. Nevertheless, arid areas have recently been attracting increasing attention from hydrologists to explore their characteristics and to study appropriate modelling techniques. There are studies carried out in the arid parts of USA, Australia, Africa and the Middle East that can be used as guides for those and other arid parts of the world. The paper highlights some problems that can be faced in modelling rainfall-runoff in arid areas through reviewing experience using different model types and discusses some aspects that need to be considered in such kind of studies.

Keywords: rainfall-runoff modelling, arid zone hydrology, rainfall-runoff model types.

Introduction

Arid areas have many distinctive features that differ from those of humid areas. The high temporal and spatial distribution of the rainfall, flash floods, absence of base flow, sparsity of plant cover, high transmission losses, high amounts of evaporation and/or evapotranspiration and the general climatology, are some of the differences in hydrological features between the arid and humid areas. In addition, the quality of data is also poor in many arid areas due to the sparse rainfall and runoff networks, difficulties in accessing the flow gauge sites during storm events, the high variability and irregular occurrence of the flow, the lack of control sections in the changeable flow channels and the difficulty of direct measurement of the flow with the high sediment and debris loads.

Modelling is a very important tool that enables hydrologists to make more comprehensive use of rainfall time series. Modelling rainfall-runoff in arid areas can be considered as a key component of studies of the dynamical aspects of arid-zone hydrological processes (Ye et al., 1997). Rainfall-runoff modelling is also useful in flood and water resources assessment as these models can generate a long representative time series of stream flow discharges from which water supply or flood protection schemes can be designed (Beven, 2000). Furthermore, rainfall-runoff modelling aids hydrologists to understand the hydrological processes much better. There is also a need to extrapolate from the available measurements to assess the likely impact of future hydrological change which can be carried out with aid of modelling. Thus, rainfall-runoff modelling is an important field of science that needs more investigation and effort to improve suitable modelling methods for different area types.

Arid areas have generally received much less attention than humid areas. Relatively few watershed models have been tested to check their validity when applied in arid areas; even fewer include modifications to consider the special hydrological characteristics of arid areas. Furthermore, the number of models particularly developed for arid areas is very limited. Much more work is needed to investigate model performance and suitability.

However, hydrological modelling in arid areas is not an easy task as the hydrological characteristics of arid areas are not yet fully understood and, as mentioned above, most models were initially developed to consider wet area hydrological characteristics. Therefore, studies on rainfall-runoff modelling in arid areas face some difficulties that need to be discussed to be understood to be overcome, bearing in mind that it is very important to select suitable models that consider the hydrological characteristics of arid areas, the available data and serve the aim and the purpose of the modelling.

1. Hydrological characteristics of arid areas

The hydrological characteristics of arid areas are different in some important aspects from those of humid areas. It is very important to understand these differences to accommodate them in any developed model or to modify the selected model. The section below highlights some of these features.

1.1 Climate

The climate in arid areas, e.g. temperature, radiation, humidity, evaporation, evapotranspiration, and rainfall regime, is very different from that of humid areas. The different rainfall patterns and seasonality have particularly important consequences for the hydrological characteristics of arid areas (Rodier, 1985; Pilgrim et al, 1988; Al-Qurashi, 1995).

Evaporation is one of the climate characteristics that affect the hydrological processes in arid and semi-arid areas. It is determined by the temperature, wind velocity, radiation and humidity. The high temperature and high radiation inputs give very large values for potential evaporation and high evaporation losses from open water surfaces. The limited availability of rainfall is a key control on actual evapotranspiration.

The average annual relative humidity varies from region to region and depends on distance from the coast. Humidity can be very high in coastal areas (up to 90%) and much lower in inland areas (up to 40%) (MWR, 1995).

1.2 Rainfall

Rainfall in arid areas has different characteristics from that of humid areas and it is very important to understand these characteristics when carrying out modelling. Rainfall is generally sparse in arid areas and there could be many years without any significant rainfall but on the other hand there could be some wet years with several severe events.

In many arid areas, the dominant mechanism of rainfall generation is different from humid areas as most of the storms result from squall lines and convective cloud processes producing storms typically of short duration, relatively high intensity and limited areal extent. These fall on bare land, with limited or sparse vegetative cover, which generates Hortonian excess overland flow that can be enhanced by surface crusting (FAO, 1990; Wheater et al., 1997). However, other mechanisms are also possible and may predominate in some areas. In Oman, e.g., cold frontal troughs can cause some rainfall in winter.

One of the most important rainfall characteristics in arid areas is the spatial and temporal variation of rainfall. The rainfall tends to be more variable in space and time (Pilgrim et al, 1988, Wheater et al, 1991a, b; Al-Qurashi, 1995). Rain gauge densities in Walnut Gulch in USA, for example, which are about 1 per 2 km^2, showed highly localised rainfall occurrence with spatial correlations of storm rainfall of 0.8 at 2 km separation, and close to zero at 5-20 km spacing (Wheater and Weshah, 2002). Studies in Saudi Arabia and Oman showed similar results (Wheater et al, 1991a, b; Al-Qurashi, 1995).

Seasonal effects were clear from some studies carried out in different arid areas. The winter and summer rainfall in arid areas were found to be different in characteristics (Al-Qurashi, 1995; Hofman and Rambo, 1995; Drissel and Osborn, 1968). The summer events seem more intense with short duration and more localised than that of winters and the generated floods can be severe, resulting in very high and flashy floods, causing great damage.

1.3 Runoff

In most arid areas, there are no continuous flows and the flow channels are generally dry for most of the year but very flashy floods are expected after short intense rainfall. Flows may last for a period ranging from a few hours to not more than a few days. As noted above, the predominant runoff mechanism is generally believed to be Hortonian overland flow, where the rate of rainfall exceeds the potential rate of infiltration (Pilgrim et al, 1988; Wheater et al, 1997). In combination with high intensity, short duration and convective rainfall, extensive overland flow is expected to be generated. The generated runoff is likely to be highly localised in space and reflect the spottiness of the spatial rainfall fields and to occur on only parts of a catchment (Walters, 1989; Wheater, 2002).

The hydrographs in arid and semi arid areas tend to be flashy with short time bases and steep rising and falling limbs (Pilgrim, 1988; Walters, 1989; Wheater and Brown, 1989; Al-Qurashi, 1995). This is demonstrated in Figure 1.

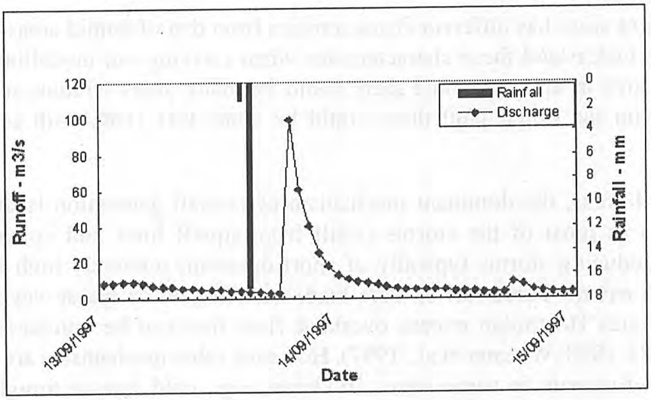

Figure 1: Flash Flood at Wadi Ahin near Hayl, Sultanate of Oman

It should be also noted that even though floods are rare in arid areas, when they do occur, they tend to have very large peak discharges and a considerable runoff volume. The occasional severe floods in an otherwise arid environment can cause considerable damage to both life and property. Various events are reported in the literature. Up to 1650 m^3/s was observed in the Southern Negev and Sinai (Schick, 1988). However, in Oman much higher peaks were observed. In Wadi Dayqah in 1927, a massive peak outflow of 9,500 m^3/s was determined whereas in another occasion a peak of about 10,600 m^3/s was estimated in Wadi Ghudun in 1977 flood event (MWR, 1998, 2002).

1.4 Channel Transmission Losses

Transmission losses are a very important phenomenon in studying stream flow and groundwater recharge in arid areas. Understanding and assessing transmission losses is important in modelling both surface and groundwater. Due to this phenomenon, water is lost, as flood waves travel through the normally dry stream channel systems or networks. Thus, runoff volumes and flood peaks are reduced (Renard et al, 1966, 1970). Transmission losses are also an important component of the water budget because surface water yields are reduced, riparian vegetation and wildlife are supported, and local aquifers are recharged (Sorman and Abdelrazzak, 1993). Therefore, prediction of flood peaks and calculation of water budgets for watersheds in arid areas require quantification of the impacts of transmission losses on components of the hydrologic cycle (Jordan, 1977; Lane et al., 1971; Lane and Asce, 1990). Unfortunately, this phenomenon is not well understood so far.

1.5 Vegetation Cover

The vegetation in arid and semi arid areas is very sparse and has a great variation from one location to another and from one time to another as it depends on the rainfall. The density of vegetation may be very different after a wet period from that after a prolonged dry period. Rodier (1985) showed that in valleys the vegetation can become dense after rainfall, and this impedes the flow during floods. There is also a wide variation in the soil water balance at a scale related to plant spacing (Pilgrim et al, 1988). The interception varies greatly with time and space in arid and semiarid regions due to the variation of the vegetation cover which complicates the description of the process and modelling of interception (Pilgrim at el, 1988).

The vegetation cover has an important effect on infiltration and recharge besides the flow velocity, interception, and evapotranspiration. The range of the vegetation attributes is likely to have a greater impact on the runoff and soil water aspects in arid areas than is the case for humid regions. The sparse coverage of vegetation has also a great effect on soil erosion as it can lead to high runoff coefficients and sediment loss. Vegetation cover has some effects on other parameters that can affect the hydrological responses of the watershed such as the roughness coefficients, the soil characteristics and evapotranspiration. Hence, it affects both effective rainfall and runoff.

1. Types of rainfall-runoff model

There are many different models that are used currently and the number is increasing as the science is developing and computer power is advancing. There are many ways to classify models. Models can be classified based on process description, scale, and technique of solutions (Singh, 1995). They can be classified also based on land-use (agricultural, urban, forest and rangeland, desert, mountainous, coastal, wetland, mixed) or model-use (planning models, management models, forecasting models) (Singh, 1995). Below is a brief discussion of some of these types.

2.1 Spatial Representation

Based on this criterion, the model can be classified as lumped, distributed or semi-distributed.

- **Lumped models:** In lumped models, the hydrological processes are represented in a spatially integrated form (Wagener et al., 2004). Spatial variability of processes, inputs, boundary conditions and watershed geometric characteristics are not taken into account (Singh, 1995).

- **Semi-distributed models**: A lumped representation is used for individual sub-catchments, and the sub-catchment outputs are combined and routed to represent the catchment as a whole. Thus inputs and catchment properties can be represented as spatially-variable over the catchment, but aggregated over the individual sub-catchments. Many lumped models are also used in semi-distributed form, e.g. HEC-1, RORB, SWMM and NWSRFS.

- **Distributed models:** In distributed models such as SHE and IHM, the governing equations of motion are solved using a spatial grid and hence variability of processes, inputs, boundary conditions, and/or watershed characteristics are taken into account (Singh, 1995). However, it should be noted that spatial-averaging of processes occurs at the scale of the spatial grid used.

2.2 Time-Scale Based Classification

Models can be classified based on the interval of the computation, such as continuous-time or event based, then according to the time interval used, as for example, hourly, daily; monthly, and yearly (Singh, 1995).

2.3 Model-Structure Based Classification

Wheater et al. (1993) classified models into three main types, based on the model structure and the use of data (see also Wheater, 2002).

• Metric Models

These types of models are based solely on observed data and seek to characterise system response from those data. A well-known example is the unit hydrograph (Sherman, 1932), although currently much more powerful methods of systems analysis are available (see Young, 2002). A major strength of the method is the power of analysis. For example, for the unit hydrograph, once the storm flow and effective rainfall components of an observed response have been separated, a unique unit hydrograph can be identified and hence the event response can be characterised. The variability of the unit hydrograph can be established by analysing data from a range of events. Unit hydrograph characteristics for gauged catchments can be related to catchment characteristics and hence a method derived to represent ungauged catchment response (e.g. NERC, 1975). Due to lack of local data, regional unit hydrograph methods, based on US data, have been widely applied. The best known is the USDA Soil Conservation Service (SCS) method, which has been incorporated into catchment models such as the US Army Corps of Engineers HEC1 package. In turn, such packages form part of wider modelling systems, such as the Watershed Management System (WMS, 1996). An interesting and typical application for flood protection of Petra, Jordan is reported by Al-Weshah and El-Khoury (1999). While undoubtedly convenient, the use of such methods without calibration on local data must always be open to question, and sadly, little work is available to critically evaluate their performance in arid and semi-arid areas. This remains a research priority.

• Conceptual Models

This type of model represents all of the component hydrological processes perceived to be of importance in catchment-scale input-output relationships (Wheater et al., 1993). The essential feature of this model type is that the model structure is specified a priori, according to the perception of the important component processes. Model parameters do not have a direct (physically-measurable) physical interpretation, hence to represent the system of interest, parameters must be adjusted through calibration against observed data. A general problem arises in that model complexity commonly exceeds the information content of the available data. One result is what has been termed 'equifinality' (Beven, 2000). Many different sets of parameters (and many different model structures) can give equivalent performance. This has been a major obstacle to application to ungaiuged catchments, but recent developments in Hybrid Metric-Conceptual (HMC) models (as defined by Wheater et al. (1993)), have led to success in application to the ungauged catchment problem (Wagener et al., 2004).

• **Physics-Based Models**

This type of model represents the component hydrological processes in a more classical mathematical-physics form, based on continuum mechanics, through numerical solution of the relevant equations of motion using a finite difference or finite element spatial discretisation (Wheater et al., 1993). Hence the parameters are in principle measurable physical properties. However, it is not generally possible in practice to measure the parameters at the scale of the model grid, hence there will be a large number of unknown parameters that need to be estimated for any specific catchment, which affects the uncertainties of the model parameters and performance. In principle, such models can be applied to ungauged catchments and to the prediction of catchment change; in practice performance using uncalibrated parameters has generally been found to be poor (Wheater, 2002).

3. Some modelling experiences in arid areas and difficulties encountered

Various different model types have been used in arid conditions, and some of these studies are mentioned below to highlight some of the difficulties that were encountered. A general experience is that aridity has an influence on the model performance (e.g. Mimikou, 1983, 1992; Chiew and McMahon, 1994). It is more difficult to obtain good model performance for drier environments.

• **Use of Metric Models**

In a study on the Walnut Gulch watershed, Osborn and Renard (1973), explain how difficult it is to develop rainfall-runoff relationships from small watershed data. The authors carried out analysis of two major runoff events which showed that the hydrographs were very different, due to different storm intensities, durations and spatial extent. In another study, Osborn and Lane (1971) developed a method for predicting the outflow hydrograph volume and peak discharge using the volume of the inflow hydrographs. The regression equation and the gamma distribution that was used to represent the outflow hydrograph shapes, were found to work better with a single peak event but not for multiple peaks.

Unit hydrograph methods were found to have difficulties in some respects. Wheater and Brown (1989) carried out a study on one of the wadis in Saudi Arabia to test the performance of the unit hydrograph method in the region. Individual unit hydrographs showed high variability, and even after extensive analysis, no consistent relationship could be determined to explain the variability of the unit hydrograph in terms of rainfall or antecedent conditions. The results of an overall unit hydrograph obtained from a combined set of all the events were also found poor. One of the greatest difficulties faced in this study was the selection of suitable runoff coefficients. The range observed varied from 5.9 to 79.8%. The analysis could not explain the scatter in the rainfall-runoff volume relationship in terms of rainfall depth, maximum intensities, temporal distribution or antecedent conditions. The authors concluded that the problems arose due to the highly localized rainfall, which was not characterized by the available raingauge network, and transmission losses.

Catchment characteristics such as catchment size, shape, slope, and catchment infiltration rate all have some effects on the accuracy of model results (Nouh, 1990). Nouh (1990) in his study in Saudi Arabia used the geomorphological instantaneous unit hydrograph (GIUH). The model accuracy was found higher with catchments with low infiltration rates and catchment areas of less than 400 km^2. Hence, Nouh (1990) recommended not to use the GIUH model for large catchments or conditions of high infiltration loss. The spatial and temporal variation of the rainfall was found to affect the performance of the model, and the length of the dry inter-storm periods also has some effect.

On the other hand, Sorman and Abdulrazzak (1993) used the same model (GIUH) using 13 representative catchments in Saudi Arabia aiming to determine the flood hydrograph under an arid climate due to its importance in water resources assessment. The authors illustrated that Philip's infiltration model cannot be used directly as determining the runoff coefficients in arid areas is more complicated and changes from one wadi to another as well as from one event to another (Sorman and Abdulrazzak, 1993; Al-Qurashi, 1995). On the other hand, the calibration of the model showed that the model is sensitive to the values of the saturated hydraulic conductivity and flood wave velocity, which were difficult to be measured in the field. It was also found that the soil porosity, pore-size index, and saturated hydraulic conductivity, velocity, and ground water table levels are the most dominant parameters in estimating the flood hydrographs.

• Use of Conceptual Models

MODHYDROLOG is among the conceptual models that were tested in arid conditions. Chiew and McMahon (1994) have carried out a study on 28 catchments in Australia with different climate regimes. The study shows clearly that it is more difficult to simulate runoff in semiarid and arid catchments when compared to wetter catchments, due to the processes governing the relationship between rainfall and runoff in arid catchments, where runoff is a small proportion of rainfall and where streams are ephemeral. It was difficult to determine the values of some of the important model parameters and therefore calibration against stream flow data was required. Another important finding was that, although MODHYDROLOG generally gives satisfactory estimates of runoff, it has some difficulty in simulating runoff after long periods of zero flows, a characteristic of ephemeral streams in arid catchments. Therefore, questions are posed concerning the suitability of using this model in arid areas, but this is likely to be a general problem of conceptual continuous simulation models.

The Pitman model (Pitman, 1973) is a monthly conceptual model, widely used in South Africa. Hughes (1995) explained that the model seems to have some problems when used in the more arid zones. The problems were grouped by Hughes into two main categories; those related to the way in which the model represents catchment runoff generation processes and those associated with the nature of the rainfall input to the model The model was found to have problems regarding its capability to allow for generated upstream sub-catchment runoff to be lost through re-absorption into storage lower down the catchment, and regarding its capability to allow for vegetation changes due to the variations in seasonal rainfall amounts. When the model was applied to the Nata River in Botswana, it was found that a reasonably acceptable fit between simulated and observed flows could only be obtained by setting the storage and absorption parameters for the upstream areas to values much higher than the lower sub-area. The results illustrated again some of the difficulties of using this type of model in semi-arid catchments. The author also illustrated the problems of modelling severe events using this model. Large events are important in arid areas and can strongly affect average runoff, and hence are important for flood and most water resource studies.

The VTI model, using a daily time-step (Porter and McMahon, 1971) was tested in Botswana (Hughes, 1995). Hughes illustrated that the most important element of the model is its ability to generate runoff either by infiltration excess processes or by saturation excess. Also this model has a transmission loss routine that allows water that has reached the channel system to be re-infiltrated if sufficient capacity exists in the transmission loss storage zones. However, the model is semi-distributed and needs the catchment to be divided into sub-areas but there was little information to indicate if the main model parameters need to be different across the sub-areas and there was no information to quantify any differences (Hughes, 1995). Hence, it was found that the only differences in the parameter values were related to the position of the sub-areas within the total catchment. Accurate definition of the rainfall input to the sub-areas was problematic due to the distribution of the rain gauges. This is a general problem for arid areas.

The IHACRES Model (Jakeman et al., 1990, 1994; Jakeman and Hornberger, 1993) was tested, in some catchments in Australia. The model is considered as a HMC model of average complexity. Ye et al (1997) explained that in the low-yielding catchments examined in this study and for catchments with no regular base-flow, only one linear store is needed to explain stream-flow and using a single store required only one additional parameter to those in the loss model. The results were found reasonable when used with daily data, but the performance increased when used for monthly analysis. IHACRES was found of adequate performance in all tested cases. The interesting finding was that its performance was higher for the dry periods. IHACRES has been modified in various other studies (e.g. Evans and Jakeman (1998), Post and Jakeman (1999), Croke and Jakeman (2004) but more investigation is needed to check the validity of the modified versions.

The LASCAM model (Sivapalan et al., 1996a, b) has been developed to predict the impact of land use and climate change on the daily trends of stream-flow and salinity in the forested water supply catchments of southwestern Western Australia. The model considers the unique soils and climate of the region and is sensitive to all the hydrological processes operating in the water supply catchments. Ye et al (1997) used this model to check the performance of conceptual rainfall-runoff models in low-yielding ephemeral catchments that ranged in size from 0.82 to 517 km^2. The results of the study showed that LASCAM provided the best model fit statistics overall when compared to the GSFB and IHACRES models.

Wheater et al (1995) developed a simple distributed continuous simulation conceptual model for water resource evaluation in Oman, based on the SCS method for runoff production and incorporating a distributed transmission loss component. The model performed well for the limited data availability (2 calibration events), and was applied to test scenarios of resource development using a stochastic rainfall generator to represent spatial rainfall inputs. However, more extensive testing using longer data sets is required.

• Use of Physically- based Models

Physical-based models need data that must in principle be measured directly (or in practice estimated) for the catchment. Such data can very rarely be found in arid areas. The KINEROS model was developed mainly to be used for the arid parts of the USA (Kibler and Woolhiser, 1970; Rovery, Woolhiser and Smith, 1977; Woolhiser et al, 1990a). One of the most important features of KINEROS is its ability to consider the spatial hydrological features of arid areas (Michaud and Sooroshian, 1994). Recent developments of KINEROS include default parameters based on soil type and conditioned by experience in applications in the USA.

Wheater and Bell (1983) carried out a study using KINEROS to assess the 3 May 1981 storm that hit Wadi Aday in Northern Oman and caused severe damage. Due to lack of physical data, rainfall losses were calculated externally and the model was used to route the resulting runoff. After abstracting an initial rainfall loss, the continuing losses were represented using a runoff coefficient of 0.75 for the hard rock sub-areas, and 0.50 for the gravel hills. The results showed good agreement between the calculated peak discharge and that obtained by the model though this was achieved by calibration of rainfall losses and some adjustment of roughness coefficients.

Michaud and Sorooshian (1994a), in their study on the comparison of simple versus complex distributed runoff models on Walnut Gulch, USA, investigated KINEROS in comparison with two simpler models (a lumped and a distributed models) based on the SCS method. Overall, it was found that the simulations were disappointing for all the calibrated models in simulating both peak and volumes, though KINEROS was much better in comparison to the distributed SCS model. On the other hand, both SCS models were not able to accurately simulate peak flows or runoff volumes for individual events without calibration. However, the calibration increased the performance of the SCS models slightly. A very important finding in this study was that KINEROS cannot cope with medium to large size watersheds, which have catchment areas of more than 100 km^2. However, more investigation will need to be carried out to pin down the reasons for this conclusion as the model has been used successfully in larger catchments (Wheater, 1981; Wheater and Bell, 1983). However, Michaud and Sorooshian (1994a) found it very difficult to decide on the accepted complexity level of the models to be used in arid areas. The authors also suggested that empirical models had merits but might not be capable to deal with the new hydrological problems that are faced currently.

The different rainfall measurement uncertainties and their effect on rainfall-runoff modelling were studied by different hydrologists (Michaud and Sorooshian, 1994b; Faures et al., 1995; Andreassian et al., 2001). Faures et al. (1995) have used the research version of KINEROS model (Goodrich, 1990) to gain a better understanding on how spatial rainfall variability impacts the performance of runoff models for small catchments. The study illustrated that the percentage measurement errors can affect the smaller events more than the large events hence, the relative variations of the small events is much higher than that for larger storms. The uncertainty in runoff estimation was found to be affected highly by the number of the input rain-gauges, and the location of the gauges is believed to have a great effect in modelling the storm hydrograph. It should be born in mind that assuming a uniform rainfall depending on only one single rain gauge can lead to large uncertainties in runoff estimation (Faures et al., 1995). However, the effects of spatial and temporal variation of rainfall and runoff can be very high even for small catchments, hence caution is necessary in such cases (Wheater 1991a, b; Al-Qurashi, 1995).

4. Effects of hydrological characteristics on model performance

The above review has shown that there are a number of expected problems associated with arid areas due to their distinctive hydrological features. Furthermore, it was noted that different models can face different problems based on their structure, complexity, and the data availability and quality.

Extreme events do not occur in arid areas frequently, but it is important that they be considered in any hydrological analysis and modelling. However, extreme events can cause difficulties in most types of modelling (Wheater, 2005; Croke and Jakeman, 2005). Hence, it was suggested for regression methods that the low flow frequency events be treated separately using a different set of equations (Osborn and Lane, 1969)

Another important hydrological feature in arid areas is the hydrograph shape. The general shape of the hydrograph in arid areas has a steep rise with short recession, but different events have different unit hydrographs, dependent for example on the rainfall spatial and temporal distribution and transmission losses. These differences can cause difficulties in selecting the representative hydrograph when using metric models that depend on the unit hydrograph method (Osborn and Renard, 1973; Wheater and Brown, 1989; Al-Qurashi, 1995).

The variation of runoff coefficients in arid areas is another feature that causes difficulties in some model types. The high variation of runoff coefficients makes it difficult to select values for modelling (Wheater and Brown, 1989; Sorman and Abdelrazzak, 1993; Al-Qurashi, 1995). The transmission losses in arid areas are very high and thought to be one of the reasons why runoff coefficients can affect the hydrograph shape and recession time (Wheater and Brown, 1989). This is an important phenomenon, still not fully understood, and most models do not consider it in the model structure. Metric models that depend on the unit hydrograph method still can be considered very useful when modelling individual flood events but more sophisticated methods for continuous modelling have had little application to arid areas. In addition, such methods are not readily useable to predict effects of catchment change.

The spatial variation of rainfall-runoff is surely one of the most important features that needs to be understood and considered in modelling arid areas. However, it causes tremendous difficulties as the modeller can face runoff events when there is less or no rainfall recorded at all (Wheater and Brown, 1989; Sorman and Abdelrazzak, 1993; Al-Qurashi, 1995). Faures et al. (1995) emphasized the importance of knowledge of the spatial rainfall variability that the modeller should have on the same or smaller scale if distributed catchment modelling is to be used for small-scale watersheds.

The data availability, suitability, quality and the period of records is questionable in many cases and this can make it difficult to distinguish whether the poor performance of the model is due to the model structure or the data quality. There are many conceptual models that depend on numerous parameters to describe the hydrological processes. However, due to the high variability of the parameter values, the actual values of each location are difficult to obtain. Infiltration rates, as an example, vary greatly from one location to another, but as the values of soil physical properties are only available for certain locations, extrapolation to the whole catchment is problematic. This has a large influence on the viability of physical models. The same is true of other data such as channel storage, which is rarely available in arid areas and either has to be averaged or estimated (Hughes, 1995). Distributed models are promising from the point of view that they consider the spatial variability of the parameters but due to the limitation in data availability, estimated values have to be used for locations where data are not available.

The processes that govern the relationship between rainfall and runoff in arid areas as shown above are in some respects more complex than that in humid areas (Chiew and McMahon, 1994; Al-Qurashi, 1995). Some models such as MODHYDROLOG have faced difficulties in modelling a long period of zero flows followed by peaks (Chiew and McMahon, 1994). This is a common feature of arid areas as most the wadi channels are dry most of year except during heavy rain events. However, in some other cases, it was not easy to recognize the reasons behind the low performance of the model, as in case of VTI and GSFB (Hughes, 1995; Ye et al, 1997). On the other hand, there are some other models that obtained reasonable results such as IHACRES (Ye et al, 1997; Post and Jakeman, 1999) though the results varied from one catchment to another.

5. Conclusions and Recommendation

Arid areas have some distinctive hydrological features such as the high variability of rainfall and runoff both spatially and temporally, high evapotranspiration, high transmission losses, variable vegetation cover, etc. These features are very important for modelling arid areas.

Rainfall-runoff modelling is an important technique that could be very powerful when used appropriately both in hydrological assessment and management. Hence, this technique is an important tool to be used in arid parts of the world but needs to be used with caution due to the different hydrological features and the shortage of data availability and quality.

There are many different types of models that are currently available and the number seems to be increasing due to the high attention this field is receiving currently. Reviewing the applications of the different models and model types shows that the performance of one model can be different from another due to many factors. A model that can be successfully used in one area might not be suitable to be used in another area. Therefore, care should be taken to select a suitable model type with an acceptable level of complexity. Selecting a complex, sophisticated model might not be of any benefit if the model does not consider the hydrological characteristics of the area and the most important parameters. The suitability of the available data for the selected model is another very important factor that needs to be considered. Finally, modeller understanding and experience of the hydrology of the area and the model used is also very important.

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Construction, Calibration, and Validation of a Catchment Management Model for the Netecatchment

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CONSTRUCTION, CALIBRATION, AND VALIDATION OF A CATCHMENT MANAGEMENT MODEL FOR THE NETE CATCHMENT

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ABSTRACT

The management of the groundwater level of river valleys has become an important topic in restoration ecology. In Belgium, due to straightening of rivers and the extensive drainage of the floodplains in the past, water levels dropped drastically and river valleys lost their natural character. The falling water levels were then associated with falling groundwater tables, and the authorities decided to restore the latter through rewetting. However, the effect of rewetting on the surface water-groundwater interaction is still not understood quantitatively (C.Demetriou and J.F.Punthakey 1999). For this, hydrological models are necessary. This paper documents the development of a distributed, physically based model of the Nete catchment using the MIKE SHE code. It describes the multi-step modeling procedure that was followed, and the multi-criteria protocol adopted for calibration of the model. The model was calibrated and verified to provide forecasts of stream flow and stage data in time and space, based on past hydrological, soil, and land-use records. The paper also mentions the results of a risk assessment study carried out using the fault tree technique. These results showed that the greatest risk to the modeling is of a spatial nature or involves the field measurements. Sources of greatest risk to the modeling were revealed as originating from the spatial variability of parameters, followed by parameter uncertainty, then model structure uncertainty respectively.

Keywords: Calibration, Integrated modeling, MIKE SHE, Nete, Rewetting, WETSPRO.

1. Introduction

Over the last century, the land use map of Flanders has been dramatically altered with large areas of agricultural land being drained and put into intensive agricultural production. At the same time, Europe has experienced a number of unusually long-lasting rainfall events in the last decade that produced severe floods, e.g. in the Netherlands, Belgium, France and Germany (1993, 1995), the Czech Republic, Poland and Germany (1997), recently in North Italy (1994, 2000) and in the UK (1998, 2000) (Institute for Environment and Sustainability 2004). The issue of restoring wetland areas is now receiving increasing attention as a means of promoting the environmental benefits that are thought to be associated, including the mitigation of severe flooding. Water retention within catchments is an emerging concept that has been receiving increasing attention in the recent past as a result of the changing climatic conditions being experienced. Collective action is required for restoration of a basin as it involves the participation of the landholders and benefits from economies of scale. In addition, enhanced environmental benefits are mostly achievable at larger scales. Changing people's views on water use and making them understand the meaning and necessity of good water management requires convincing scientific arguments. Such arguments can be communicated to the parties involved through the use of examples and models. Models can also be used to answer the research questions that arise with water retention, such as, what are the risks of water conservation, to what extent should the basin be restored, and do other options exist to address the primary problem of hydrological extremes.

Hydrological models are classified according to their representation of the catchment processes as distributed or lumped. The structuring of distributed models permits spatial variation of catchment characteristics, while lumped models consider the catchment as a unit (Refsgaard, J. C. 1997). This results in distributed models having hundreds of parameters more than lumped models, and requiring more effort for model building. (Rosso 1994) categorized the problems related to model development as follows.

> "In principle, spatially distributed models can accept experimental data at each grid point. Practically, parameter heterogeneity and scale differences make parameterization very cumbersome. These constraints also apply to the validation of distributed model predictions using measurements of internal system response. Conventional strategies for distributed model validation typically rely on the comparison of simulated model variables to observed data for specific points representing either external boundaries or intermediate locations on the model grid... Traditional validation based on comparing simulated with observed outflow at the catchment outlet still remains the only attainable option in many practical cases. However, this method is poorly consistent with spatially distributed modeling."

Rigorous parameterization is crucial to avoiding methodological problems in subsequent phases of model calibration and validation (Refsgaard, J. C. 1997). Parameter spatial patterns are defined to reflect significant and systematic variation as perceived in the raw data, a process that reduces the number of unassigned parameters whose coefficients then need to be calibrated.

Because they relate model parameters directly to physically observable land surface characteristics, spatially distributed hydrological models have important applications to the interpretation and prediction of the effects of land use change and climate variability (Andersen, J, Refsgaard, J. C., and Jensen, K. H. 2001; Binley, A. M., Beven, K. J., Calver, A., and Watts, L. G. 1991; Calder 1993; Calder, I. R., Hall, R. L., Bastable, H. G., Gunston, H. M., Shela, O., Chirwa, A., and Kafundu, R. 1995; Conway, D. 1997; Jothityangkoon, C., Sivapalan, M., and Farmer, D. L. 2001; Lorup, J. K., Refsgaard, J. C., and Mazvimavi, D. 1998; Refsgaard 1987; Refsgaard, J. C., Thorsen, M., Jensen, J. B., Kleeschulte, S., and Hansen, S. 1999).

Three defining problems encountered in integrated, dynamic modeling for medium to large sized catchments include firstly, distributed physically-based models that comprise an integrated description of both surface water and groundwater processes that require a large amount of data to perform reliable simulations. Utilization of such models requires stringent parameter assessment from field data in existing databases. Secondly, the methodology for calibration is not easily discernable. Inverse modeling is widely used both in dynamic surface water hydrological modeling and in steady-state groundwater modeling. Thirdly, a model of this type basically simulates the key processes of the land phase of the hydrological cycle. However, that does not give any guarantee that the model provides accurate simulations of all processes. And even if the model can be shown to accurately simulate aggregated processes such as catchment discharge or point variables such as groundwater heads in specific observation wells, this does not in itself prove that the underlying processes are simulated with the same accuracy. Thus it is very important to derive and apply a methodology with systematic validation tests so that the validity and limitations of the model can be documented.

The paper presents and discusses the methodology adapted for the construction, calibration and validation of a hydrological model at the regional scale. It describes the multi-step modeling procedure that was followed, and the multi-criteria protocol for calibration of the model.

2. Background

2.1 Basin hydrology

The Nete river basin is located in the northeast of Belgium and has a total drainage area of approximately 385 km^2. The general pedagogical conditions are dominated by sandy loam to sandy soils. The topography is flat and varies between 12m in the west to 69m in the east and the region has a shallow water table. The area is well drained by the Nete River and its tributaries (Figure 1), and by a whole series of drains and ditches. The basin receives an annual average rainfall of 790.3 mm/year. The mean annual potential evapotranspiration is 546 mm/year, while the mean annual discharge is 374.8 mm/year (El-Nasr, Vazquez, Christiaens, and Feyen 2002).

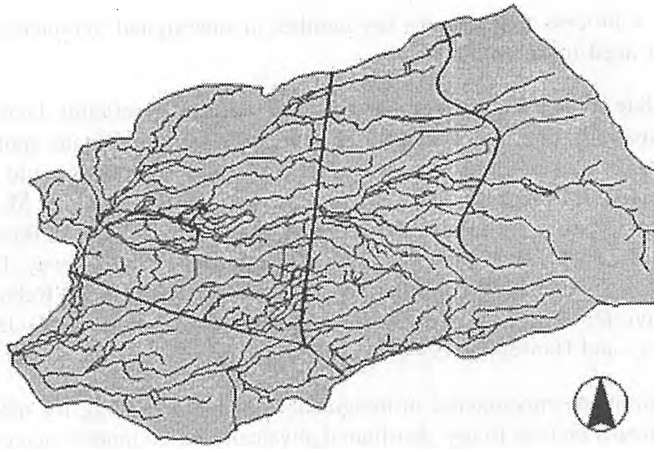

Figure 1: The study area

The land use in the catchment consists of artificial surfaces, agricultural lands, forest and semi-natural areas, wetlands, and open water bodies. In the model, these land uses were divided into categories as shown in Table 1.

Table 1: Land use distribution in the Nete basin

	Land use	Percentage
1	Paved areas	23.5
2	Bare soil	0.6
3	Grassland	20.8
4	Maize	35.7
5	Pine forest	3.1
6	Leaf forest	14.7
7	Wetlands	0.3
8	Open water	1.3
TOTAL		**100.0**

2.2 Objective

The main objective was to construct, calibrate and validate a hydrological model for the Nete river basin. This model would then be used to investigate the influence of river basin restoration and extreme hydrological events in the Nete basin. River basin hydrology is complex and dynamic with multiple flows through the different zones of the soil strata. Matching modeling outputs to ongoing monitoring would ensure further refinement of the model, and the study then envisaged a long term objective of providing the basis for adaptive water use management in the Nete basin.

3. Methodology

Model building followed a multi-step modeling procedure which incorporated an interactive multi-criteria calibration protocol (see Figure 2).

3.1 Data organization

This preliminary step involved clarification of the overall study objective as the development of a distributed model for the Nete basin. A conceptual model was then developed. with which the data needs of the study could be established. At this stage simplifying assumptions were made about the hydrology as the conceptual model was developed to reflect the understanding of the hydrological processes and model purpose. For the model, the MIKE SHE code was adopted as it incorporates all the different hydrological phases of overland flow, inter-flow and base flow. The model included five main hydrological processes, namely the river network, evapotranspiration, overland flow, unsaturated flow, and saturated groundwater flow. This first step was repeated until sufficient information was known about the basin with which a model could be developed.

3.2 Input formulation

Previous studies had established both the soils database and the vegetation parameters for the basin. An unconfined aquifer consisting of four principle layers and no geological lenses was assumed. The model incorporated the three main rivers, namely Grote Nete, Grote Laak and Molse Nete into the one-dimensional MIKE 11 model. Tributaries and drains were not meaningfully depicted at the chosen model scale of 250 X 250m. Instead, drainage from the latter two was represented by conceptual drain pipes in MIKE SHE.

Seven rainfall-measuring stations were used as sources of rainfall input, namely Dessel, Mol, Geel EA25, Geel EA53, Westerlo, Kwaadmechelen, and Kleine-Brogel (Figure 3). The modified Penman equation was used to calculate potential evapotranspiration for a closed, short-cut grass surface supplied optimally with water. Input data for this was provided by the Royal Meteorological Institute of Belgium (RMI).

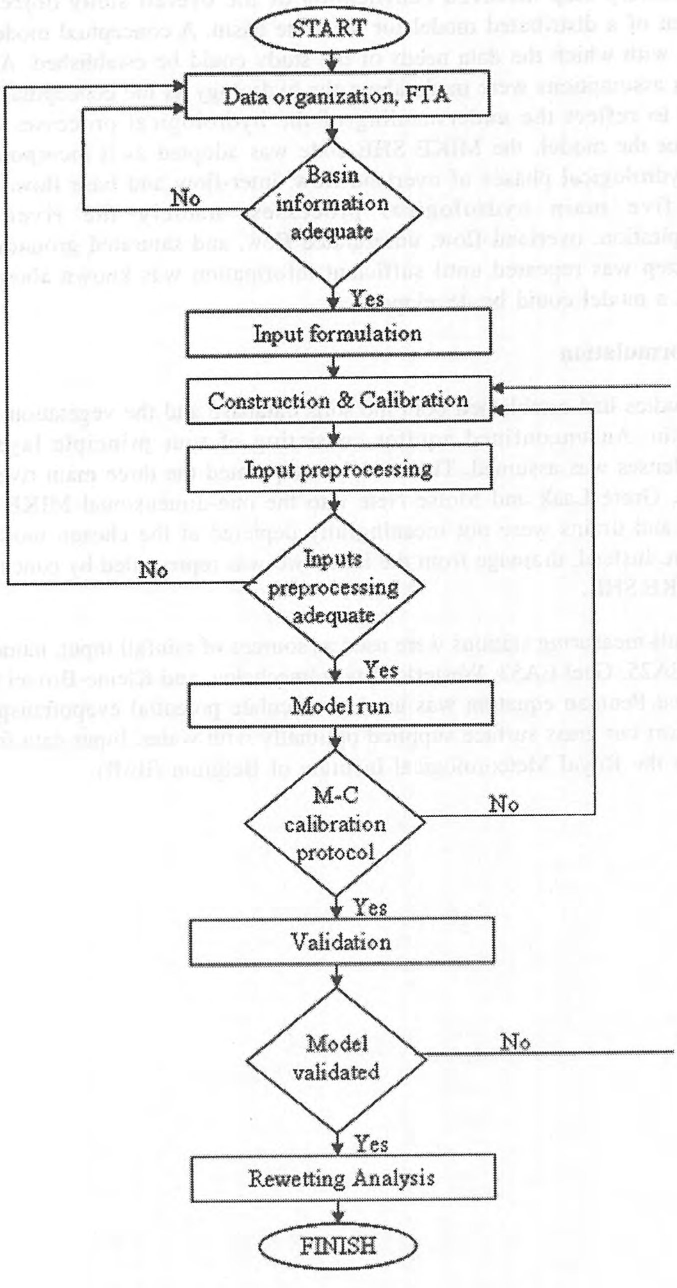

Figure 2: Multi-step modeling procedure

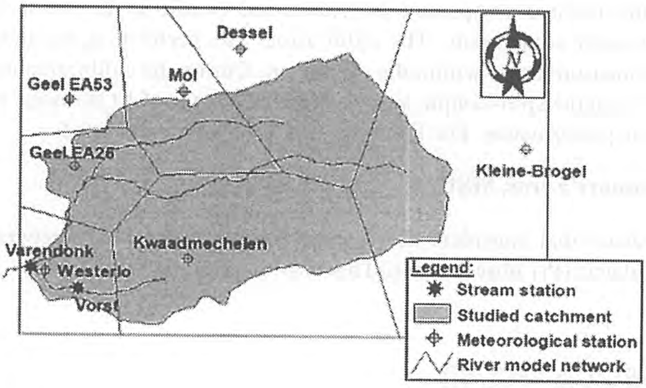

Figure 3: Rainfall measuring stations and corresponding Thiessen polygons

3.3 Construction and calibration

The model was spatially partitioned at a scale of 500 X 500m, and in some cases 250 X 250m where there was sufficient information. Boundary and initial conditions were established, and parameterization was undertaken. Vertical partitioning of the vadose zone varied from an initial 0.025m in the top nodes to 1m at the bottom.

Model simulation specifications were included for the time step control, simulation periods, and computational control parameters. Grid input files were developed for topography, land use, groundwater levels, saturated layers, and pumping wells. Both field data and literature were used to derive parameters, which were then assigned as required in the Graphical User Interface.

3.4 Input preprocessing

The previous stage involved specifying input data required by MIKE SHE, including definition of boundaries. At this actual stage model spatial data to be used during model simulation and input errors are evaluated and displayed by MIKE SHE. Where missing or erroneous input data was identified, the process of data organization was resumed. Consequential to the dynamic nature of time series during simulation in response to stresses on the system, they are not considered in this procedure. If input preprocessing revealed sufficient input data, MIKE SHE was then run.

3.5 Multi-criteria calibration protocol

Hourly discharge data is available for the Varendonk discharge station for the period beginning January 1986. The model was calibrated against data over the period 1986 to 1989. River dredging is known to have been carried out in the vicinity of the gauging station in mid-1989 (2001), and consequently data over a 6 month period is excluded from use.

Water Engineering Time Series PROcessing tool (WETSPRO), a tool for time series analysis (Willems P. 2003), was used in this research for implementing the multi-criteria calibration protocol. This model incorporates a recursive digital filter for exponential recessions (Breuer L., Eckhardt K., and Frede H.G. 2003) to split total rainfall-runoff discharges into its three component sub-flows, and is able to determine the recession constants for each component. The calibration was performed manually based on multivariable measurements within the catchment. During the calibration and validation of the model, both the split-sample approach and goodness-of-fit statistics were adopted as measures of performance. For the latter, the following were used:

3.5.1 Mean Square Error, MSE

This is a measure that considers the average random discrepancy between measured (Oi) and simulated (Pi) observations. This was determined as:

$$MSE = \frac{\sum_{i=1}^{n}\left(BC(Oi)-BC(Pi)\right)^2}{n}, \tag{1}$$

Where the Box-Cox transformations on the measured and simulated observations were defined as:

$$BC(Xi) = \frac{Xi^{\lambda}-1}{\lambda} \tag{2}$$

The value of λ for this catchment was previously determined as 0.25 (Vazquez, Willems, Feyen, and Berlamont 2004). The Box-Cox transformation is used in determining the MSE in order to counter the effects of extremes (Box, G. E. P. and Cox, D. R 1964). This is due to the fact that the MSE is sensitive to extreme values, and assigns more weight to errors during high flow periods. Peak Over Threshold values were used for this analysis. This was done to avoid attributing too much weight to low flow events, as these events cannot be truly independent of each other as they are governed by base flow variations.

3.5.2 Correlation coefficient, R^2

The correlation coefficient is a quantity that gives the quality of a least squares fitting to the original data. A linear relationship was expected between the observed and simulated values. The linear least squares fitting technique is the simplest and most commonly applied form of linear regression and provides a solution to the problem of finding the best fitting straight line through a set of points.

3.6 Validation

The model was validated using the split-sample method, utilizing data from the Varendonk station over the period 1990 to 1995. Validation was done using WETSPRO with the aid of the following plots: modeled vs. observed discharge maxima during (nearly independent) quick-flow hydrograph periods; modeled vs. observed discharge minima during (nearly independent) base-flow or slow-flow hydrograph periods; cumulative flow volumes; High flow extreme value statistics; low flow extreme value statistics; and discharge time series, with and without log-scale for the discharge.

4. Results and discussion

A model of the Nete catchment was built in the MIKE SHE code. A fault tree analysis was first carried out to describe a methodology for incorporating various kinds of dependencies in the modeling process. Many of these dependencies arise naturally and their correct analysis is crucial to the accurate assessment of the model system reliability. The analysis established the presence of only one minimal cut set. A review of the critical paths shows that the greatest risk to the modeling is a result of the spatial variability of the model parameters over the catchment, which reflects as an inherent uncertainty due to the model's limitations in representing the parameter heterogeneous distribution. The next three leading causes of uncertainty were found to be of an epistemic nature, and were the temporal variability of parameters, scale approximations in modeling, and human error, respectively.

A number of models had to be built during the calibration process, the different input parameters being varied for each model. The simulated hydrographs from each were inputted into WETSPRO, and Extreme Value analyses were applied to the models. The Varendonk station was used for split-sample calibration of the model parameters, during which process a multi-criteria calibration protocol was followed. This protocol obtained simulated and observed discharge hydrographs that were acceptably similar. The individual flow components of the rainfall-runoff discharge were well simulated. Furthermore, the recession constants of the simulated individual flow components were comparable to those from the observed hydrograph. Values of $MSE < 0.2$ were obtained, along with $R^2 > 0.8$. Figure 4 shows part of the measured and calibrated hydrographs for the discharge measurement station at Varendonk. Figure 5 shows the equivalent hydrographs for base flow as obtained from the recursive digital filter. This calibrated model was then taken to represent the existing state.

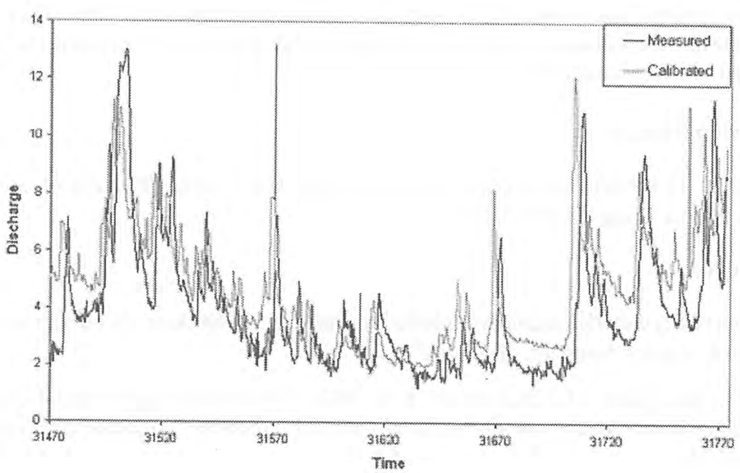

Figure 4: Hydrographs of measured and calibrated total discharges in m^3/s

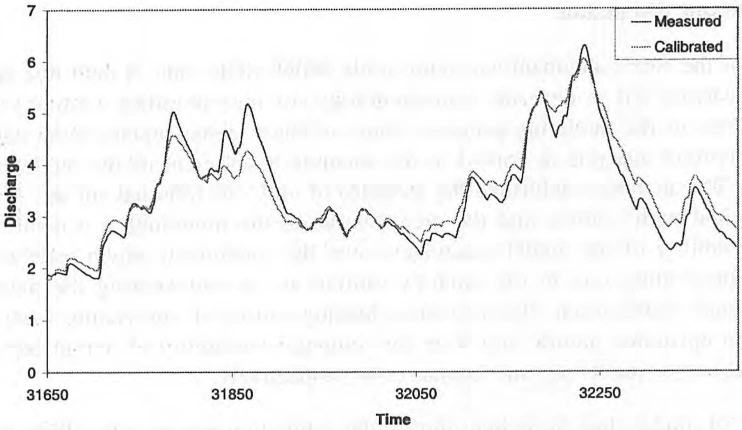

Figure 5: Hydrographs of measured and calibrated base flow discharges in m^3/s

With the 3-dimensional flow model that was built for the Nete catchment it is now possible to simulate and study the surface water - groundwater interactions that naturally occur in nature. The fault tree analysis technique was applied and found to be a valuable aid to understanding the uncertainties within the model.

5. Conclusions

First, it is now possible to better understand the interactions between the hydrological processes in the Nete catchment. This is an important prerequisite for the next phase of this research, which deals with defining the influence of rewetting on extreme river flow events and the effect on flood risk. A number of models were built, manual calibration being conducted to determine the appropriate improvements to subsequent models. While model efficiency could not be used to compare the different models (K.Eckhardt and J.G.Arnold 2001), the MSE with Box-Cox transformations was employed, as part of a multi-criteria protocol. The results of this study indicate that the protocol is effective in determining the best model where correct modeling of individual sub-flow components is of consequence.

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