

Multi-Objective Optimization for Sustainable and Integrated Groundwater Management in Arid Regions

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Abstract

Increasing demands for water by competing users in arid regions pose new challenges for water resources managers. Decision makers must understand the interactions between surface water, groundwater, and the environmental system. Additionally, the decisions made with regard to groundwater management and allocation must take into consideration the diverse objectives that include water supply, cost efficiency, and ecosystem protection. The work presented herein demonstrates the use of groundwater simulation and optimization to construct a decision support system (DSS) for solving groundwater management problems in the GCC countries as an example for an arid region. In GCC countries, groundwater is abstracted at a faster rate than the renewable aquifer system can be naturally recharged. The total annual of groundwater abstraction is about 19572 million cubic meters, however the recharge is about 4875 million cubic meters. The results are falling water tables, saline water intrusion into fresh aquifer systems, water quality deterioration and mining the nonrenewable aquifers. The case is treated as a multi-objective optimization problem in which environmental objectives are explicitly considered by minimizing the magnitude and extent of drawdown within a pre-specified region. The approach adopted uses the constraint method to derive the tradeoffs among three competing objectives. Once the proposed algorithm identifies a set of efficient solutions (alternatives), concepts borrowed from fuzzy set theory are applied to rank the alternatives and to assist decision makers in selecting a suitable policy among them, each of which is optimum with regard to its goal and the corresponding consequences.

Keywords: Groundwater deterioration, Modeling, DSS, GIS, Water demand, Water management, Cost analysis, Database.

Introduction

In arid environments, groundwater is an important and precious resource for municipal and rural supplies, eco-environment maintenance, and social and economic development especially where no surface water is available. Protection and integrated management of groundwater resources along with other available resources and understanding of the interactions between groundwater and human activities are crucial for sustainable water resources development and planning on a regional scale.

The Gulf Cooperation Council, GCC, countries experience a severe water shortage problem, that threatens the sustainable development and hinders the national plans for human, industrial and agricultural development. The territories of the six member states of

GCC countries (Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates) occupy most of the Arabian Peninsula; an area of huge reserves of crude oil and gas. Figure (1) presents the geographical location of the GCC countries in the Arabian Peninsula. Oil production constitutes the cornerstone for the economic strength of this region. The living standard in the GCC countries is relatively high.

GCC countries are a part of water competitive world and water deficit grows larger with each year, making it potentially more difficult to manage. GCC countries have extremely dry climate with rare rainfall, high evaporation rates and limited non-renewable groundwater resources. Conventionally available water supplies on renewable basis in these countries are simply insufficient to meet the increasing water demands of the present modes of economic activities and resource exploitation. The six countries that comprise the GCC occupy a total land area of 2.7 million km² and their combined population is currently over 30 million and is expected to top 40 million by 2010. Over the last quarter of a century there has been a three and four-fold increase in population and total water use respectively. At the start of the 3rd Millennium, all GCC countries, except Oman (583m³/cap/yr) fell in the critical water scarcity category; < 500 m³ renewable water/cap/yr. Total water demands are expected to increase 36% over the next decade.

Today the total annual groundwater abstraction is about 19572 million cubic meters, however the recharge is about 4875 million cubic meters. The results are falling water tables, saline water intrusion into fresh aquifer systems, water quality deterioration and mining the nonrenewable aquifer which is about 91% of the combined total water demand, 7.2% by desalination of ground and sea-water and the remainder from treated effluent and surface water. On average, agriculture accounts for 85% of all water used and the current deficit of water resources is estimated at 15 Billion m³. All GCC countries are becoming increasingly dependent on the non-sustainable mining of local groundwater aquifers that are presently threatened by pollution and depletion. In addition, governmental policies with regard to increasing the level of food self-sufficiency through subsidies and other incentives, have contributed to a major expansion in and unrestricted use of non-renewable groundwater resources. This makes it essential to start giving a serious consideration for non-conventional water resources for their full potential development.

The scarcity of water resources and the increasing gaps between demand and available supply in the Gulf Cooperation Council (GCC) countries is a major challenging issue facing the development sectors. This coupled with a lack of defined policies and strategies geared toward optimizing and managing the scarce water supplies within the GCC region, have contributed to wasteful and uneconomic practices, as well as to the inefficient mining of non-renewable supplies. Nowadays, all GCC countries have made substantial progress in their respective campaigns for water resources management over the last decade, especially in the area of development of non-conventional water resources. However, increased cooperation and collaboration, both internally and externally (e.g. through the recently formed GCC Water Resource Committee) within and amongst the member countries is urgently required in order to satisfactorily implement the numerous action plans that have been called for within water resources country policies and strategies.



Figure 1: General Location Map for GCC Countries.

In an area of increasing demand of water resources such as GCC countries new paradigms of better knowledge about the relations among available water resources and environmental objectives make it peccary to devise innovative decisionmaking tools comprised of sound science, significant amounts of data and societal preferences. Groundwater simulation and optimization techniques have been used together to explore management options. Depending on the particular problem under consideration and the assumptions made in solving it, the optimization problem may be linear, nonlinear, continuous or discrete, or a combination of both. Linear programming has been applied successfully in determining optimal operational policies in water supply systems (Louie et al., 1984; Elmagouni and Treichel, 1994). Quadratic programming has been used when pumping costs depend on drawdown, usually when drawdown magnitude exceeds a small fraction of the saturated thickness (Shafike et al. 1992). Discrete optimization is required in a broad range of design problems. Fixed costs of installing new wells may be a relevant component of cost functions in groundwater planning strategies (Hsiao and Chang 2002). For sites in which complex hydrogeological conditions obscure an obvious intuitive design, simulation-optimization techniques help decision makers in shedding light over alternate feasible options (Ahlfeld and Heidari 1994).

Most of the published works to date on simulation optimization applications to groundwater management are confined to small to medium size sites. In those cases, a

single or centralized decision maker is able to define relevant objectives and preferred solutions. Multi-objective optimization has been used before for conjunctive use of surface water and groundwater. Most previous studies were applied to water quantity optimization in local regions, such as in coastal areas (Emch and Yeh, 1998) and irrigation areas (Onta et al., 1991), or specifically for economic and policy analysis (Rosa, 1995). Groundwater quality was managed for unique wastewater treatment purposes (Alireza et al., 1994), or considered as a constraint in water management (Wong et al., 1997). In the Shiyang catchment, surface water and groundwater are closely interactive and frequently exchange in pearl-string-like basins. Groundwater quality and quantity are equally important to the eco-environment. The regional, multi-step and multi-objective water management plan discussed herein has complicated constraints in terms of water quantity, quality, economics and eco-environmental aspects. Therefore the groundwater flow and quality have been simulated first; then a multi-objective optimization scheme with objectives of groundwater level, quality and quantity and eco-environmental aspects has been developed. The response matrix and embedding techniques are usually used to couple groundwater models and optimization models (Duckstein et al., 1994; Yang and Lin, 1993). Peralta et al. (1991) argued that a steady-state embedding model required less processing time than a response matrix model. However, for regional problems with a greater number of objectives, the embedding model is not suitable because the constraint matrix may become too large (Yeh, 1992). The research reported herein showed that the response matrix model was more flexible and memory saving for the multi-period, multi-objective programming of the regional water resources management and was thereby used to couple the groundwater simulations into the multi-objective optimization model.

When applying systems analysis to a large-scale problem, however, new difficulties arise. First, generally there exists more than one decision maker, and therefore numerous conflicting objectives can be defined. Second, the number of decision and state variables may increase rapidly with the scale of the problem, increasing the computational burden of obtaining optimal solutions. Third, large-scale systems cannot be treated as lumped systems, and spatial dependence of the problem must be considered when defining objectives and constraints. Furthermore, from a policy perspective, decision makers are faced with the problem of devising management tools to deal with decision variables that may not be under centralized management. For example, hundreds or thousands of small private pumping wells may exert significant stress on the aquifer system, but may be very difficult to manage coherently. When a decision maker can define a problem and articulate the objectives for its solution, it is said that the problem is well structured. In many cases, although an ultimate abstract objective may exist, complex spatial problems are ill- or semi-structured and decision makers find it difficult to fully articulate their objectives (Densham 1991). In such circumstances, traditional prescriptive analytical techniques may prove unsatisfactory to decision makers, and therefore more flexible interactive approaches should be sought.

The approach presented herein employs a multi-objective optimization to solve the conflicting eco-environmental problems for sustainable development of the groundwater resources in the GCC countries as an example for arid regions. The overall objectives were to: (a) maintain current water utilization in the short term and meet water supply requirements in the long term; (b) minimize groundwater quality deterioration and control, eliminate and alleviate hazards that are caused by overexploitation of groundwater, based

on prediction trend; (c) meet increasing water demand for domestic, agriculture, forestry, and industry uses; and (d) achieve the best social, ecological, environmental and economic values of water use. Extensive data on regional water resources, hydrogeology and other environmental factors have been accumulated, which provided a solid basis for the multi-objective management and protection of water resources.

1. Groundwater in GCC Countries

1.1. Groundwater Aquifer Systems

The GCC countries are located in an arid region. In such arid environment with rare rainfall and no surface water bodies are available, groundwater is an important and precious resources for municipal and rural supplies, eco-environment maintenance, and social and economic development. Protecting and sustainable integrated management of this valuable resource, understanding of aquifer system, recharge mechanism, past and present abstraction and human activities is crucial for developing the management policies on regional scale.

Groundwater aquifers systems in the GCC countries can be classified to two main systems. The first is the shallow renewable aquifers comprise of shallow alluvial deposit layers with high yield at the north, east and south of the Arabian Shield. The thickness of the alluvial deposits varies from about 20 to 200 m with the exception of the aquifer in the coastal area of Oman where it reaches about 400 m. The width of these alluvial deposits varies from few hundred meters to several kilometers. The recharge of the shallow alluvial aquifer systems is very limited. The average annual recharge varies between 70 mm and 140 mm. The average annual volume of rainfall water is estimated at 205.93 Billion m³ (ACSAD, 1997). However, most of this water can not be directly harvested or utilized because of the flat and sandy dunes areas along with the high evaporation rate. 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. The quality of water in the alluvial aquifers is generally good with total dissolved solids between 250 and 4000 ppm. Seawater intrusion is encountered along the coastline of the Arabian Gulf due to intensive development activities and groundwater exploitation in the coastal areas. The reserved water in the numerous aquifers of the sedimentary basins are fossil groundwater derived from earlier Quaternary intervals of much greater rainfall. The total reserve in the alluvial deposits is estimated at 115.5 Billion m³, of which 84 Billion m³ are encountered in the largest single alluvial reservoir of Saudi Arabia (Khouri et al., 1986; Ukayli and Husain, 1988; Abdulrazzak, 1993). The dependable groundwater reserves are those encountered in the thick extensive sequences of sedimentary formations of the Arabian Shelf underlying two-third of the GCC countries as shown in Figures (2) and (3).

The second is the non-renewable deep aquifers comprise of fractured igneous and metamorphic rocks which provide extensive and permeable areas for surface runoff and shallow Wadi underflow (Alsharhan et al., 2001). Most of deep aquifer system are not explored. Groundwater reserves in the deep aquifers of the Arabian Shelf are estimated at 2330 billion m³, while the average annual recharge rate is estimated at 2.7 billion m³ as shown in Table (1). Over 30% (740 billion m³) of groundwater reserves is encountered in the Wasia-Biyahd aquifer. The groundwater reserves, in this context, are estimated as the volume of pumped water when the water levels or piezometric heads are lowered to a level of 300 m below the land surface. The total volume of groundwater extracted from the deep

aquifers in the area over the last two decades is estimated around 300 billion m³, of which 254.5 billion m³ were pumped from Saudi Arabia alone to satisfy the needs for the expansion in the agriculture sector. The recharge of the deep aquifers during the last two decades was limited to 54.0 billion m³. About 76% of the total groundwater recharge in the GCC countries is encountered in Saudi Arabia, while 15% is encountered in Oman.

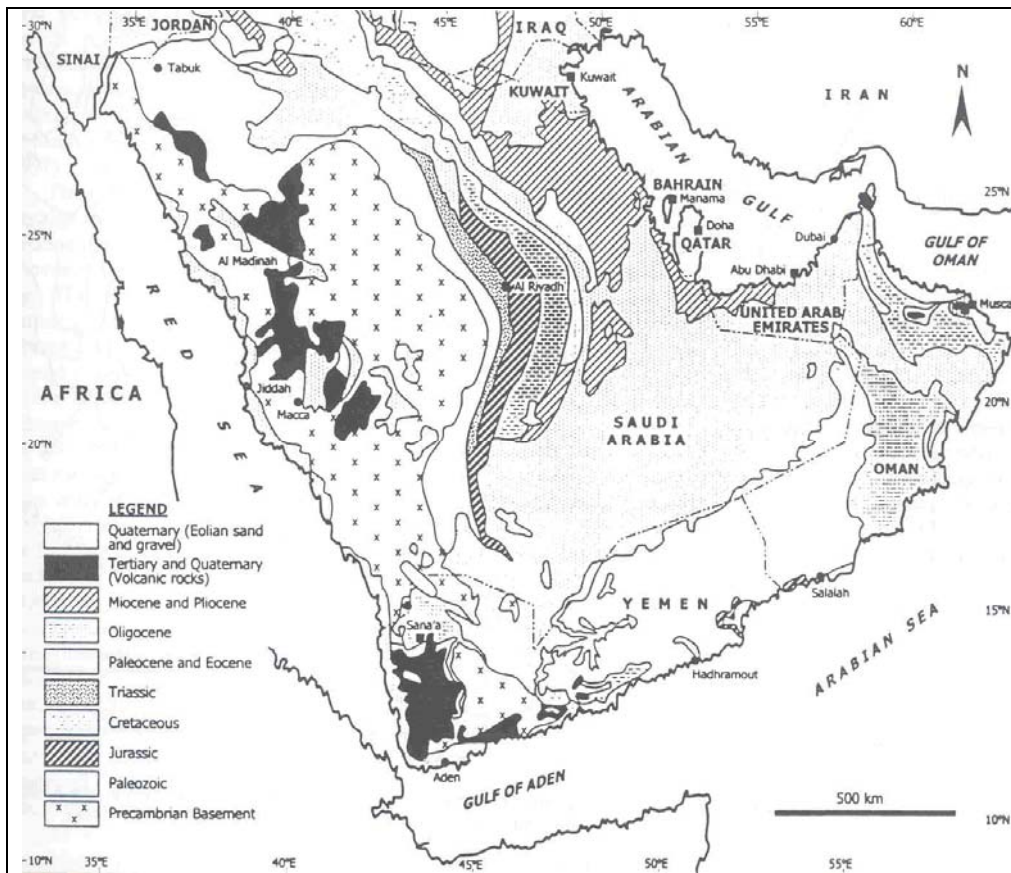


Figure 2: Simplified geological map for the Arabian Peninsula (after Alsharhan and Nairn, 1999)

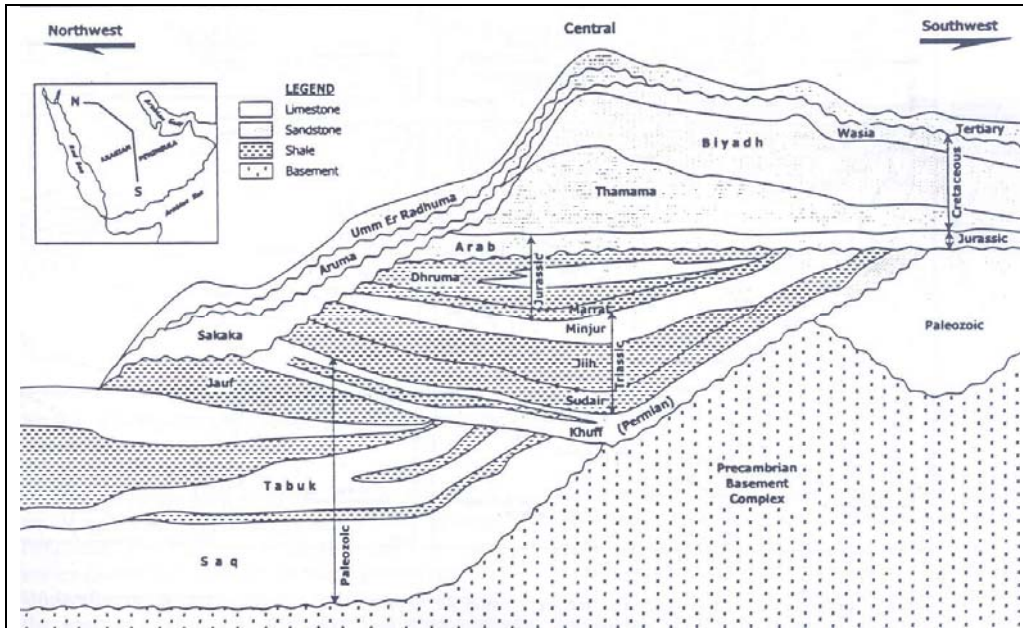


Figure 3: Schematic cross section in the Arabian Peninsula (after Al Alwani and Abdulrazzak, 1997)

Table 1: Groundwater reserves in the deep aquifers and its quality.

Aquifer Name	Total reserve (million m ³)	Annual Recharge (million m ³)	Total dissolved solids (mg/l)
Main aquifers			
Saq	227,000	310	300-1500
Tabuk	205,000	455	200-3500
Wajid	225,000	104	500-1200
Minjur-Dhurma	182,000	80	1100-20,000
Wasia-Biyadh	240,000	480	900-10,000
Um Er Radhuma	188,000	406	2,500-15,000
Dammam	25,000	200	2,600-60,000
Neogene	130,000	290	3,700-4,000
Secondary aquifers			
Khuff and Tuwail	30,000	132	3,800-6,000
Aruma	85,000	80	1,600-2,000
Jauf and Sakaka	100,000	95	400-5,000
Jilh	113,000	60	3,800-5,000
Total	2,330,000	2,692	

1.2. Groundwater Abstraction

Table (2) shows that the total annual groundwater recharge in GCC countries is about 4875 MCM. Groundwater abstractions during 2002 exceeded the annual replenishment of about 14697 MCM which is about 75%. Thus, considerable groundwater mining takes place, mainly for irrigation use. Because of the overexploitation, the actual contribution of groundwater to the total use in the region is more than 75%. At country level, groundwater abstractions are currently the main source of water in the GCC countries. Overall, the contribution of groundwater abstractions to total demand ranges from less than 68% (in Kuwait) to more than 90% (in Bahrain). The groundwater is mainly used in agriculture and forestry sectors (Dawoud, 2006).

Table 2. Renewable Water and Groundwater Use in the GCC Countries (year 2002).

Country	Population (x1000)	Renewable Water Resources (MCM)			Ground water Use (MCM)	GW significance, in terms of:	
		Surface water	Groundwater	Total		% of renewable GW to total renewable water	% GW use to total demand (year 2000)
Bahrain	677	0.2	100	100.2	258	99.80	91.49
Kuwait	2165	0.1	160	160.1	405	99.94	68.64
Oman	2518	918	550	1,468	1644	37.47	89.01
Qatar	599	1.4	85	86.4	185	98.38	53.31
Saudi Arabia	21930	2,230	3,850	6,080	14430	63.32	81.23
UAE	2411	185	130	315	2650	41.27	78.50
Total	30300	3334.7	4875	8209.7	19572	59.43	75.34

2. Management Framework

For sustainable and integrated groundwater resources management in the GCC countries, it is important to keep in reasonable balance the costs and benefits of management activities and interventions, and thus take account of the susceptibility to degradation of the hydrogeological system involved and the legitimate interests of water users, including ecosystems and those dependent on downstream base flow. In practical terms it will be necessary to set possible management interventions in the context of the normal evolution of groundwater development, and for this it is convenient to distinguish a number of levels. However, it must be noted that preventive management approaches are likely to be more cost-effective than purely reactive ones. The condition of excessive and unsustainable abstraction which is accruing widely now in all GCC countries (**3A—Unstable Development**), is shown in Figure (4). For this case the total abstraction rate (and usually the number of production water wells) will eventually fall markedly as a result of near irreversible degradation of the aquifer system itself.

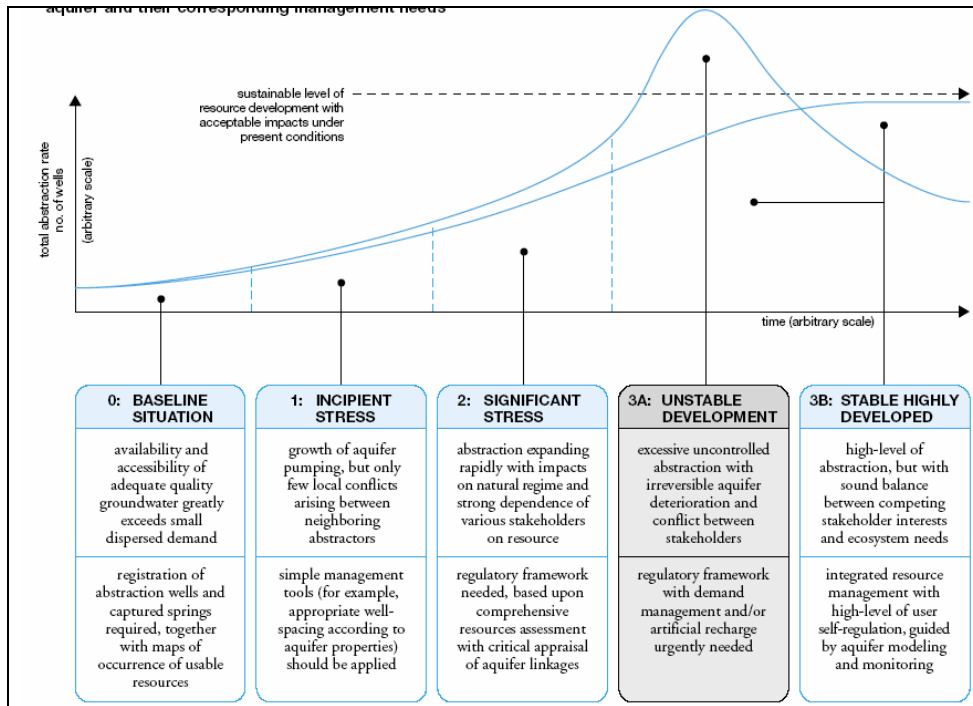


Figure 4: Stages of groundwater resource development and their corresponding management needs(after World Bank, 2002).

3. Overview of the DSS

The decision-making processes associated with the utilization of water resources are very complex, and require thorough consideration and analysis. Sectoral approaches to water resources development and management have been and still are dominant but there is need for a shift towards a holistic approach to avoid fragmented and uncoordinated policies. Additional challenges arise in the field of water policy from the multi-dimensional interactions between the various aspects of human activities, their impact on natural systems and the corresponding influence of natural responses upon the human domain.

The developed The DSS uses the concept of a water management scheme (WMS), defined as a set of scenarios for variables that cannot be directly influenced by the decision maker (i.e. rainfall patterns constituting a water availability scenario and population growth formulating a demand scenario) and the application of one or more water management interventions.

A WMS is defined in terms of a database containing information on the water infrastructure at a certain region and reference year, at which the implementation of scenarios and strategies begins. A base case is always present, serving as input for the creation of new WMSs. User interaction with the DSS falls under three functional groups, accessed via a hierarchical navigation tree: (a) base case editing, allowing for the editing and introduction of new data for the reference year; (b) creation of WMSs, providing the capabilities for defining scenarios on water availability and demand, definition of strategies

environmental) as well as benefits from water use. The Detailed Results section provides the results of the allocation in terms of appropriately customized indicators aggregated either for the entire region or presented for each type of network object. An example of the interface of the DSS is presented in Fig. 2. Finally, the Economic Analysis branch permits the selection of appropriate models and parameters for the estimation of direct, environmental and resource costs and the definition of benefits from water uses, avoiding repetition of the entire simulation procedure.

4. Multi-Objective Optimization Approach

Sustainable management of groundwater resources has gained increased attention in recent times, especially in the GCC countries. The threat of large-scale unregulated pumping has spurred the creation of groundwater conservation districts in order to regulate the underlying aquifer resources in an efficient manner. Obtaining reliable estimates for how much groundwater is available for future use is fundamental to its proper sustainable management. The available groundwater is a function of both aquifer hydrogeologic characteristics as well as the risk preferences of the decision makers' involved. In reality the optimization of groundwater management is complex problem and is of multi-dimensional. Techniques used to solve multi-objective optimization problems, are meant to identify the non-inferior set of solutions for consideration by the decision makers. This set is usually large and identifying one policy for implementation can be quite tricky. Traditionally, it has been assumed that once this set is identified, it should be presented to the decision maker who should then be left alone to make a choice of a policy for implementation. It is true that the decision maker may not even understand the numerical values presented to him in the name of optimal solutions, hence the choice of a single policy for implementation would be, at best, random. It is because of this difficulty that recently, there has been some research activate in the area of DSS. DSS are meant to assist the decision maker choose one of the presented non-inferior solution as the most satisfactory for implementation by involving him in the solution search process. The multi-objective optimization model developed here aims to define a set of best groundwater pumping and use policies in the GCC countries. Table (3) shows the objectives used to develop the management model.

The six proposed objectives and their associated tradeoffs are intended to serve as guidelines for decision makers in analyzing future options for development and ecological conservation within the region. Although for the GCC countries the major current concern is to protect the groundwater resources, the yield objective is useful for assessing the yield potential of the aquifer and the influence of development patterns. For a given groundwater exploitation pattern, it is expected that drawdown can be mitigated by increasing the cost of recharging the aquifer or by offsetting excess demand with more expensive water from other alternatives such as desalinated water or reuse of treated wastewater. Likewise, at any given cost level, the amount of groundwater to be extracted will be linked to the resulting drawdown. The optimization problem is subject to a set of constraints, which include the capacity constraints:

Table 3. Objectives used to develop the optimization model.

Objective	Function expression	Variable explains
<p>1. Minimizing the groundwater depletion: This objective aims to minimize the drawdown of the water table at any selected local area. The objective function selected to represent this goal is the l^1-norm of the differences between a target head and the simulated head at a set of selected location.</p>	<p>This function can be expressed by Equation (1):</p> $\min Z1 = \frac{1}{H} \sum_s^H [h_s^* - h_s]$	<p>Where: H = number of system states (in space and time) that are being controlled; h_s=simulated head at location s; and h_s^*= target head at location s. The selected locations are indicators of the state of the recharge from aquifer to stream.</p>
<p>2. Minimizing the net present value of groundwater depletion mitigation cost: The goal of preserving the GCC countries involves acting over groundwater exploitation patterns, as well as searching for alternative sources of water supply for these countries. Among the many water conservation initiatives that have been proposed to offset water demands in GCC countries, a subset of mitigation projects to serve as an example of how the proposed methodology can be applied to evaluate the tradeoff between cost and sustainability have been chosen.</p>	<p>The net present value of groundwater pumping mitigation is given by the expression in Equation (2):</p> $\min Z2 = \sum_{n=1}^N \left(\sum_j^U \sum_m^M CC_{j,m} \cdot Do_{j,m,n} + \sum_j^U \sum_m^M OM_{j,m} \cdot Sel_{j,m,n} \right) (1+r)^{-n}$	<p>Where: $CC_{j,m}$ and $OM_{j,m}$ = capital and operating and management (OM) costs of implementing mitigation project m at operational sector j. The binary variable $Do_{j,m,n}$ is equal to 1 if mitigation project m is implemented for operational sector j at management period n; its value is 0 otherwise. In this formulation $Sel_{j,m,n}$ is a binary variable. A value of 1 indicates that the conservation project j has been implemented at operational sector m at management period n; a value of 0 indicates otherwise. In Eq. (2) r represents the discount rate. It is assumed that once a conservation project is begun, it will continue until the end of the planning period.</p>
<p>3. Maximizing aquifer yield: One of the most important objective of to increase the groundwater aquifers yield due to the increase in demand.</p>	<p>The total amount of groundwater pumped from the aquifer can be expressed by Equation (3):</p> $\max Z3 = \sum_n^N \sum_i^S \sum_j^U q_{i,j,n}^s$	<p>Where: $q_{i,j,n}^s$ is the quantity of water pumped at well site i to supply operational sector j during management period n.</p>

Table 3 (cont.). Objectives used to develop the optimization model.

Objective	Function expression	Variable explains
<p>4. Maximizing the economic output of the groundwater use: It is very important to maximize the outcome from the groundwater water use in any development sector.</p>	<p>The negative deviation of desired total output value of outcome from the groundwater use can be expressed by Equation (4):</p> $\min Z4 = \sum D_{out}^-$	<p>Where: D_{out}^- is the negative deviation of desired total output value of outcome from the groundwater use.</p>
<p>5. Minimize the groundwater salinity (TDS): The groundwater salinity affecting the outcome from using it. Also it has a negative impact on the soil and environment.</p>	<p>The positive deviation of the TDS of groundwater at any controlling point can be expressed by Equation (5):</p> $\min Z5 = \sum \beta [D_m^+(i)]$	<p>Where: $D_m^+(i)$ the positive deviation of the TDS of groundwater at controlling points, β_i is a weighting of the water quality objective.</p>
<p>6. Minimize the investment in water development: The total amount of invest in the water sector is very important. Also, the direct link between the costs of well drilling and the groundwater salinity.</p>	$\min Z6 = \sum D_{in}^+$	<p>Where: D_{in}^+ is the positive deviation of desired investment of water development in the basin.</p>

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The six proposed objectives and their associated tradeoffs are intended to serve as guidelines for decision makers in analyzing future options for development and ecological conservation within the region. Although for the GCC countries the major current concern is to protect the groundwater resources, the yield objective is useful for assessing the yield potential of the aquifer and the influence of development patterns. For a given groundwater exploitation pattern, it is expected that drawdown can be mitigated by increasing the cost of recharging the aquifer or by offsetting excess demand with more expensive water from other alternatives such as desalinated water or reuse of treated wastewater. Likewise, at any given cost level, the amount of groundwater to be extracted will be linked to the resulting drawdown. The optimization problem is subject to a set of constraints, which include the capacity constraints:

1. Capacity constrains

The groundwater abstractions at any aquifer system within the region are not allowed to exceed the allowable aquifer capacity and well supply capacity.

$$\sum_j^U q_{i,j,n} \leq Qs_i^{\max} \quad \forall i, n$$

$$\sum_j^U q_{j,k,n}^t \leq Qt_k^{\max} \quad \forall k, n$$

$$\sum_k^T q_{k,l,n}^d \leq Qdl_l^{\max} \quad \forall l, n$$

Where $q_{i,j,n}^s$ = quantity of water pumped at well site i to supply operational sector j during management period n ; $q_{j,k,n}^t$ = rate treated at treatment facility k from user j at management period n ; $q_{k,l,n}^d$ = rate discharged from treatment facility k to discharge location l at management period n ; Qs_i^{\max} , Qt_k^{\max} , and Qdl_l^{\max} = upper bounds for extraction, treatment, and discharge rates at source i , treatment facility k , and discharge location l , respectively;

2. Drawdown constrains:

The response matrix technique was used to couple the groundwater levels with the optimization constraints. Groundwater levels were optimized for various hydrogeological and eco-environmental purposes and the drawdown of the water table at any selected local area should not exceed certain level.

$$h_{c,n} \geq h_c^{\min} \quad \forall c, n$$

3. Demand constrains :

The water demand for the various development sectors of the system should be met at any time during the optimization process.

$$\sum_i^S q_{i,j,n} + \sum_m^M Sel_{j,m,n} q_{m,j}^{mit} \geq Dem_{j,n} \quad \forall j, n$$

$Dem_{j,n}$ = demand rate at operational sector j and management period n ; and h_c simulated head at location c included in the constraint set.

4. Water quality constraints

The TDS in groundwater was identified by previous studies as an apparent identification figure for water quality in the GCC countries. The response matrix was calculated by the grey model of groundwater quality to couple the concentrations with the optimization constraints as follows:

$$B(i)[X_{gi}(i) + X_{ga}(i) + X_{gh}(i) + X_{gf}(i)] + D_c^+(i) - D_c^-(i) = C_{max}(i) - C_o(i)$$

Where:

$D_c^+(i)$ and $D_c^-(i)$ are the deviations of the TDS at the i^{th} controlling point; $C_{max}(i)$, $C_o(i)$ the maximum and original controlled indexes of TDS; and $B(i)$ the water quality response matrix calculated with a similar approach to that of Lemoine et al. (1986).

5. Economy constraints:

The primary aim of the economic analysis is the estimation, according to the results of the allocation algorithm, of financial, environmental and resource costs. A full water services cost recovery strategy. On one hand, the output values from the development sectors using the groundwater resources should reach the desired target, and on the other the investment for water development should not exceed the planned standard:

$$\sum_{i=1}^n \left\{ \varepsilon_i(i)[X_{si}(i)] + X_{gi}(i) + \varepsilon_a[X_{sa} + X_{ga}(i)] + \right\} - D_c^+ = E$$

$$\sum_{i=1}^n \left\{ \varepsilon_h(i)[X_{sh}(i)] + X_{gh}(i) + \varepsilon_f[X_{sf} + X_{gf}(i)] \right\} - D_c^+ = E$$

$$\sum_{i=1}^n \left\{ \phi_g(i)[X_{gi}(i) + X_{ga}(i) + X_{gh}(i) + X_{gf}(i)] + \right\} + D_c^- = C$$

$$\sum_{i=1}^n \left\{ \phi_s(i)[X_{si}(i) + X_{sa}(i) + X_{sh}(i) + X_{sf}(i)] \right\} + D_c^- = C$$

Where:

$\varepsilon_i(i)$, $\varepsilon_a(i)$, $\varepsilon_h(i)$ and $\varepsilon_f(i)$ are the efficiency coefficients which stand for the values produced in sub-area i by unit water uses of industries, agriculture, domestic and forestry, respectively. These were estimated by water uses and production indexes (produced values)

based on the statistical data. The terms $\phi_g(i)$ and $\phi_s(i)$ are the operation fees for using unit groundwater and surface water respectively in sub-area i , which were determined by costs of electricity, labor, boreholes, etc. The values E and D_e^+ are the desired target for the total output values of industries and agriculture and its positive deviation, respectively; C and D_c are the desired investment standard of the water development and its negative deviation in the basins, respectively.

5. Testing the Optimization Model

The developed methodology has been applied to the GCC countries. The main goal is to visualize the tradeoffs between sustainability of groundwater use and economic and development considerations. In order to evaluate the influence of different basic assumptions on the results, three policy-analysis options for utilizing the groundwater resources in the GCC countries have been tested as shown in Figure (6):

- planned schemes in which the mining of aquifer reserves is contemplated from the outset, usually for a specific development project in an arid area with little contemporary groundwater recharge
- an unplanned basis with incidental depletion of aquifer reserves, as a result of intensive groundwater abstraction in areas.
- Using other alternative sources such desalinated water for domestic and reuse of treated wastewater for agriculture and forestry.

For the evaluation procedure, environmental performance is based on the groundwater Exploitation index, which should not exceed the upper limit of 75%. The results indicated that the optimal alternative is the planned schemes. However using other alternative sources such desalinated water for domestic and reuse of treated wastewater can relief the pressure on the groundwater sources. The groundwater aquifers system is hydraulically connected and over abstraction from an area may affect the aquifer in other areas. Groundwater pumping should, therefore, be practiced within a framework of an integrated groundwater policy. Every country may, however, adopt its own policy for expansion in desalination plants, wastewater treatment and utilization of the groundwater resources. Conservation techniques should therefore be enforced in the various water consumption sectors with specific reference to the agriculture sector. Artificial recharge of groundwater should be practiced whenever possible. Water pricing for the different consumption sectors in which the tariff increases with the increase of the consumption rate will certainly benefit the water conservation exercise.

Summary and Conclusions

Obtaining reliable estimates for groundwater availability is vital for efficient management of groundwater resources. The managed available groundwater in an aquifer is a function of both aquifer characteristics and public policy. Optimization models can be established with specific management objectives (such as maximize groundwater extraction for economic gains) subject to environmental, ecological, and social constraints. The response from the developed DSS can be used to characterize these constraints, and the combined simulation optimization models can be used to estimate groundwater availability and evaluate other policies. The general simulation optimization approach has been

discussed in this paper and strategies for utilizing groundwater in the GCC countries have been evaluated. The optimization approach effectively automates this procedure and searches for all possible solutions and as such is superior to conventional sensitivity analysis. The optimization approach is also valuable from the policy standpoint, as it requires relevant stakeholders and decision makers to identify and characterize goals, objectives, and constraints. Application of this DSS is an interactive tool that can help decision makers to understand the economic, environmental and ecological implications of proposed policies and help reach consensus-based groundwater management objectives. The application of the Water Framework Directive requires the interpretation of the goals of equity and financial and environmental sustainability in a set of comprehensive indicators, which can facilitate the actions of the authorities involved.

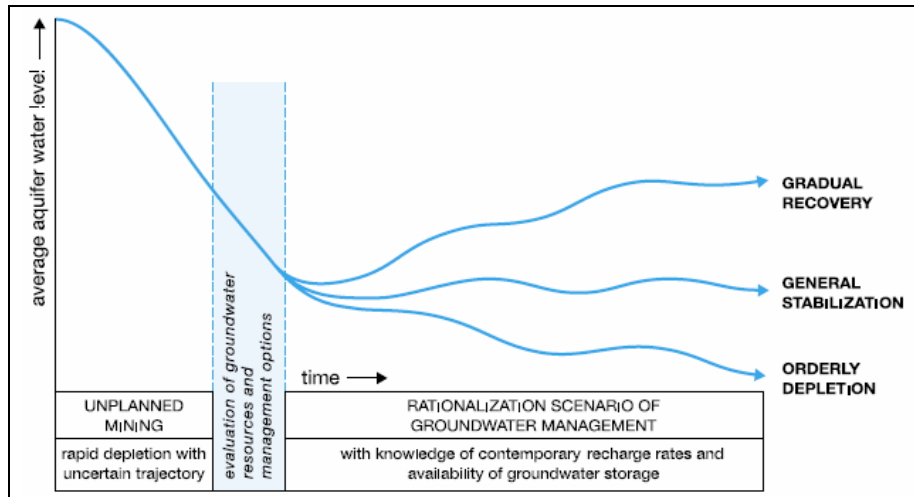


Figure 6: Targets for groundwater resource management in 'rationalization scenarios' following indiscriminate and excessive exploitation (after World Bank, 2002)

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التقييم الأمثل متعدد الأهداف للإدارة المتكاملة والمستدامة للمياه الجوفية في المناطق الجافة

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إدارة الموارد المائية - مركز بحوث البيئة البرية - هيئة البيئة - أبوظبي - الإمارات العربية المتحدة

تعد الزيادة في الطلب على الموارد المائية للوفاء باحتياجات القطاعات التنموية المختلفة تحدياً كبيراً عند تخطيط وإدارة الموارد المائية في المناطق الجافة. ومن أجل الوصول إلى تخطيط أمثل وتنمية مستدامة فإنه يجب فهم العلاقة بين جميع المصادر المتاحة ودراسة الاحتياجات الحالية والمستقبلية لمراكز الطلب على هذه الموارد. وتعتبر موارد المياه الجوفية أحد الموارد الهامة في المناطق الجافة إن لم تكن الوحيدة في بعض هذه المناطق. لذا فإن إدارة الخزانات الجوفية يجب أن تأخذ في الاعتبار احتياجات الإمداد بالموارد المائية ونوعية المياه المطلوبة والجدوى الاقتصادية والآثار البيئية. وتقدم هذه الدراسة نموذج لإدارة الخزانات الجوفية في المناطق الجافة من خلال استخدام النمذجة العددية والتقييم الأمثل متعدد الأهداف لبناء نظام لدعم متخذي القرار لحل مشاكل إدارة المياه الجوفية في منطقة الخليج العربي كنموذج للمناطق الجافة.

وتعاني دول الخليج العربي من شح في مواردها المائية نتيجة لوقعها في حزام المناطق الجافة وانعدام الموارد المائية السطحية دائمة الجريان كالأنهار وقلة الأمطار مع زيادة الطلب على الموارد المائية في القطاعات التنموية المختلفة نتيجة الزيادة المرتفعة في معدلات التنمية وخصوصاً بعد ظهور النفط. وقد أدى ذلك إلى الاعتماد بشكل رئيسي على الخزانات الجوفية والتي تكون في أغلب الأحيان غير متجددة أو اللجوء إلى المصادر المائية غير التقليدية مرتفعة التكلفة مثل التحلية. وقد وصل إجمالي السحب من الخزانات الجوفية بالمنطقة في عام 2004 إلى حوالي 19750 مليون متر مكعب سنوياً في حين تصل التغذية الطبيعية لهذه الخزانات إلى حوالي 4875 مليون متر مكعب فقط. وقد أدى هذا السحب الجائر وغير المخطط إلى هبوط مناسيب المياه الجوفية بهذه الخزانات وبالتالي ارتفاع تكلفة الضخ من هذه الخزانات. كما أدى ذلك إلى تدهور نوعية المياه الجوفية

وبالتالي التأثير على أولويات استخدامها. وسوف يتم من خلال هذه الدراسة وضع نموذج ونظام لدعم متخذي القرار في الوصول إلى إدارة متكاملة وتنمية مستدامة للموارد المائية الجوفية مع الأخذ في الاعتبار جميع العوامل الفنية والاقتصادية والبيئية. وبعد إنشاء النموذج تم صياغة واختبار عدد من سياسات التنمية والبدائل لإدارة الخزانات الجوفية بالمنطقة وترتيبها باستخدام هذا النموذج لمساعدة متخذي القرار في اختيار الأسلوب الأمثل من بينها للوصول إلى تنمية مستدامة وإدارة متكاملة لهذا المورد الحيوي بالمنطقة.