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Desalination 136 (2001) 83–92

DESALINATION

www.elsevier com/locate/desal

Evaluation of non-conventional water resources supply in Jordan

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Received 3 July 2000; accepted 17 July 2000

Abstract

The severity of the water problem in Jordan was realized in the beginning of the 1980s. Many strategies and measures were proposed to alleviate and overcome this serious problem. These mainly include supply augmentation measures through constructing of various hydraulic structures and groundwater exploitation. In addressing supply management, it was concluded that no single supply could remedy the nation's water shortage. Rather many integrated actions are needed to ensure water availability, suitability, and sustainability. Among those options is the development of new water resources such as brackish water. It was proposed that desalinated brackish water could increase water supply in different regions of the country. This paper describes the development of a decision-support system for the evaluation and selection of potential non-conventional water resources supply; these include desalination of brackish and seawater, treated waste water, importation of water across boundaries and water harvesting. Using the Analytic Hierarchy Process (AHP), it was concluded that water desalination was ranked the highest, i.e., the most promising resource, followed by water harvesting.

Keywords: Jordan; Multicriteria analysis; Water harvesting; Wastewater; Desalination; Importation

1. Introduction

Jordan is located in an arid to semi-arid zone; weather conditions are severe; and variation in related hydrological parameters such as rainfall, runoff, and evaporation is wide. They vary from day to night, from summer to winter, and from one year to another.

As the water resources in Jordan are limited, the threat of water shortages is not something that merely looms into the future. Water shortages are already a reality. Depletion of non-renewable water resources due to overpumping from exploited aquifers is also a serious problem. Consequently, the degradation of water quality due to increasing salinity is taking place.

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Presented at the conference on Desalination Strategies in South Mediterranean Countries, Cooperation between Mediterranean Countries of Europe and the Southern Rim of the Mediterranean, sponsored by the European Desalination Society and Ecole Nationale d'Ingenieurs de Tunis, September 11–13, 2000, Jerba, Tunisia.

PII: S0011-9164(01)00168-0

The population growth rate in Jordan is 3.6%, and it is considered one of the highest at the global level [1]. The population is estimated to be around 6.5 million in the year 2010 [2]. With such a population growth rate compounded with relatively fast development, an increase in water demand and waste water production is expected. The rapid socioeconomic development is, to a certain extent, adversely affecting water resources by extensive water uses in industry, agriculture, and domestic purposes.

Based upon previous studies and detailed observations [3–10], the authors conclude that there is a need now to focus greater attention on the future impact of water resources planning and development. An efficient water plan should be developed now and take into consideration all related issues. It would consist of, in addition to the adverse climatic conditions, limited water resources, high population growth, desertification and urbanization, rapid industrial growth, soil salinity, environmental sustainability, imbalance between socioeconomic development and water availability, and the effect of political instability on regional cooperation among shared water countries.

Based upon comprehensive information on Jordan and the problems and constraints, there is a serious water problem; the demand is exceeding the supply, although all conventional sources have been developed. There is a clear necessity for developing non-conventional water supplies, and there should be a high alert towards the need for conservation, management, and efficiency-enhancement measures within the water sector, i.e., an action plan should be developed and enforced: overall integrated water resources planning and development.

In this paper, using a decision-support system through a multi-criteria analysis, i.e., the AHP, an attempt was made to assist decision-makers to evaluate the various available non-conventional water resources in terms of economic, technical, availability, reliability and environmental sustainability.

2. National water resources

Jordan's fresh water resources are limited, except for a few small streams — the Zarqa, Yarmouk and Wadi Shuib Rivers — which are used for irrigation, and the Jordan River, which was used to discharge around $1.4\times10^9 m^3$ annually into the Dead Sea before the development of the water resources in its catchment area outside Jordanian jurisdiction. The Jordan River originates in Syria and Lebanon and flows to Lake Tiberias before most of its water is transferred for municipal and irrigation purposes via the Israeli National Water Carrier [11,12].

The principal water source in Jordan is rainfall, which occurs solely during winter. It supplies the water storage reservoirs and charges the underground aquifers. The annual, renewable fresh water resource is about $1.1\times10^9 m^3$. However, the amount that is exploited is $10^9 m^3/y$. Approximately 50% of this is taken from the available surface water resources. The remaining represents the sustainable yield that can be extracted economically from renewable and non-renewable groundwater resources, which are presently being exploited. The most important non-renewable groundwater resources are the Disi and Shedia sandstone fossil aquifers in southeastern Jordan: $7\times10^7 m^3$ of fresh water is extracted annually from Disi for agricultural purposes as well as for domestic purposes for the city of Aqaba. The sustainable yield over 100 years of all non-renewable ground water resources in the country has been estimated at $1.4\times10^8 m^3/y$. [13].

3. Supply and demand

In Jordan, sustainable supplies of renewable water are limited, whereas demand is rising rapidly. In 1997, the water demand was $9.5\times10^8\,m^3$. Of this, approximately $4.5\times10^8\,m^3$ was taken from surface water resources and the rest from renewable and non-renewable ground water sources. At the current rate of water demand, the differences between the national supply and demand, i.e., the water shortage, is met by over-extraction of ground water from renewable aquifers at a rate of $\sim1.8\times10^8$ to $2\times10^8\,m^3/y$ [14]. This corresponds to about 160% of the sustainable yield from the aquifers. The resulting depletions of these aquifers have led to decreases in their yields and reductions in their water quality, i.e., salination has occurred, as well as the dehydration of nearby wetlands, such as what has occurred at the Azraq oasis.

Approximately $2.4\times10^8\,m^3$ of water was used for domestic purposes during 1998 [15]. The calculated per capita domestic water use in Jordan is only $0.08\,m^3/d$: this is extremely low compared with $0.15–0.30\,m^3/d$ in neighbouring countries. The minimum quantity of water required to sustain human life has been estimated to be about $0.025\,m^3/d$ per capita, i.e. $10\,m^3/y$, and a reasonable domestic supply to maintain acceptable health and sanitary conditions could be between 0.10 and $0.20\,m^3/d$ per capita, i.e., $40–80\,m^3/y$, compared with $0.30–0.40\,m^3/d$ in developed countries [6,7]. It can be seen that Jordanians use almost the minimum amount of water, not only because they are extremely concerned about water use, but more importantly because of water shortages. Less water being available could damage public health and lead to economic and environmental disasters.

The maximum domestic water demand always occurs during summer, from May to September, due to the dry climate, high temperatures as well as being the holiday season for a large number of returning Jordanians who normally work in the Gulf States; yet no rainfall occurs during summer and so water storage is essential.

The agricultural sector is the major consumer

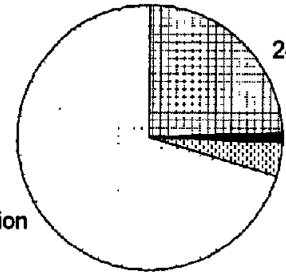

Fig. 1. Sectorial distribution of water consumption during 1998.

of fresh water; its consumption accounts for more than 70% of the total fresh water demand (see Fig. 1). This is because (1) most agricultural crops are irrigated inefficiently by surface and ground water and (2) misuse of the fertile highlands, which receive more than 300 mm of rainfall annually, due to urbanization; thus dry regions, now under cultivation, require more water per unit of yield, i.e., more than two to three times the normal rate of irrigating water because of the poor soil quality and higher evaporation rates there.

Jordanian farmers are well aware of the importance of water. Therefore, despite the high cost of implementing drip irrigation exactly when and where required, at root level instead of traditional surface irrigation, this more effective technique is now being adopted on a large scale in the Kingdom.

The industrial sector in Jordan used $5\times10^7\,m^3$ of water in 1998: a major part of this was consumed by large industries such as phosphate mining; the production of potash, cement, ceramics and soft drinks; as well as the energy sector. Almost all local industries have suffered from shortages in water supplies during the last two decades. Hence, they have usually improved water-usage effectiveness by recycling their waste water streams wherever feasible. The water shortage is also the limiting factor for the establishment of new industries as well as the expansion of certain high rate-of-water-consumption processes such as oil-shale processing, e.g., retorting, and paper manufacture as well as the utilization of fertile land for food production. For example, the annual cost of the water deficit in 1995 was estimated to be about US $95 per capita [16], which is almost same as the cost of oil imports for that year [17]. This deficit resulted from importing agricultural and food products, which could have been grown in Jordan if there had been sufficient water.

The energy-sector industries, i.e., crude oil and natural-gas extraction, crude-oil refining and electric-power generation, use less than 1% of the nation's annual fresh water supplies [18]. Such a low rate of water consumption is achieved by adopting effective and appropriate designs, e.g., dry air-cooled condensers and seawater cooling systems as at Aqaba, instead of evaporative water-cooling towers. For this reason all expansions of major industries and energy facilities and future projects are located at Aqaba.

4. The water balance and expected future demand

The present annual water demand amounts to 10% of the yearly total rainfall on the country (see Fig. 2) [14]. Almost all the economically viable surface water resources in Jordan have been harnessed, mainly for irrigation purposes. The few remaining sources will be relatively expensive to develop. The ground water resources of the country are over-exploited; some basins have been completely depleted and the rest, if present trends persist, will run dry within a few years. The depletion of groundwater resources is increasing the salinity of the remaining available water in them and so actions are urgently needed to prevent this over-pumping.

Currently, it is estimated that sustainable annual water supply per capita in Jordan is approximately 200 m^3. Increasing water demands for domestic and industrial purposes are expected as a result of the high population growth rate (see Table 1), and improvements in living standards and the planned and expected developments in the tourism and industrial sectors. The amounts of water used for irrigation may have to be reduced in order to satisfy such needs. Increased effectiveness in irrigation and reallocation from irrigation to other uses could provide sufficient renewable water to meet the growing domestic demand, at least for the next decade.

The predicted water deficits are high and increasing. Because some potential renewable resources are so expensive to harness, the volume of economically available water is far lower than what could be harnessed annually [15,19]. Jordan is likely to suffer severe water-rationing early this decade.

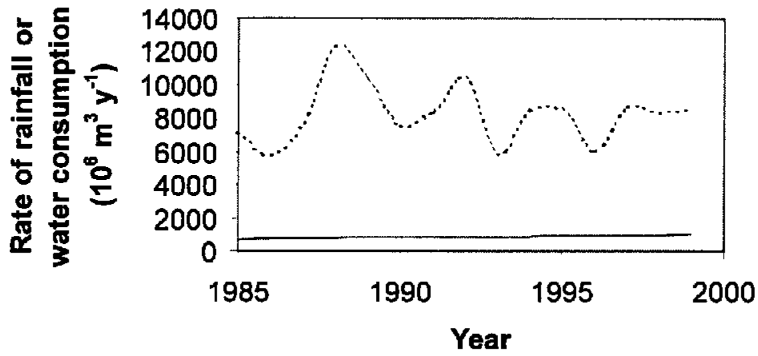

Fig. 2. Annual water demand and rainfall.

Table 1
Annual water demand predictions (10^6 m^3)

Year	Population (millions)	Municipal demand	Industrial demand	Agricultural demand	Total demand	Available resources
2000	4.9	265	5	850	1190	1020
2005	5.7	310	100	855	1265	1150
2010	6.5	350	120	900	1370	1200
2020	8.5	450	185	900	1535	1300

Water losses from the supply network, which suffers from both corrosion and damage, are significant. The unaccounted-for-water associated with the municipal and industrial network exceeds 50%, and is most likely to be due to leakages and overflows from reservoirs, unreliable meters and meter-reading problems. The overall water losses in the agricultural sector are estimated to be 45%. These losses are unacceptably high in view of the existing water shortages [5,14]. Thus, the government must act quickly to reduce such losses. This will not only save water, but also the energy being consumed to pump it up from deep wells.

5. Non-conventional water resources options

Different non-conventional water resources are considered as a potential water supply in Jordan. These include treated wastewater, water harvesting, importation of water across boundaries and desalination of brackish and seawater. Moreover, water conservation and demand management options are being considered as a means to address the water crisis in the country. A brief description of these resources is presented below.

5.1. Treated wastewater

This resource constitutes an important non-conventional source in the country. To complement the existing wastewater treatment plants in Amman, Zarqa, Salt and other cities, plans are underway to upgrade and construct 23 more treatment plants to serve an additional 34 cities and villages in Jordan. These plants will have a combined capacity of 6.6×10^7 in the year 2000 and 1.1×10^8 by the year 2010 [20]. Extensive plans and studies are underway to assess the feasibility of using treated water for irrigation in areas adjacent to the treatment plants. Although at present around 5.2×10^7/y is used for restricted irrigation purposes.

5.2. Water harvesting

Rain-water collection and storage schemes on large and/or small scale should be encouraged because in the long term these schemes would have an important role in securing sustainable water supplies in the Kingdom. It is estimated that the developed quantities of water harvesting will reach 6×10^6 by the end of this year [21]. Net additional water conservation gains for rainfall/runoff water harvesting from residential and industrial roofs was estimated to be around 4.3×10^6 and 9.5×10^6 for the years 2005 and 2010, respectively [22].

5.3. Importation of water

Preliminary studies have been conducted to assess the possibilities of importing water to

Jordan. A study was completed in 1983 to import 1.6×10^8 from the Euphrates River in Iraq to supply the northern part of the country. Another major water importing project is the Turkish Peace Pipeline, which is intended to divert the water of the Ceyhan and Seyhan Rivers in southern Turkey to supply Jordan and other countries with the fresh water [23]. The major concerns with regard to importing water are political uncertainty and security of supply as well as high capital expenditures encountered in such multi-national projects.

5.4. Desalination

Desalination of sea and/or brackish water seems to offer a sound alternative to arid lands bordering seas or salt lakes; desalination plants producing up to several million m^3/d are commercially available and have already been used for domestic and industrial purposes in some very arid regions around the world.

In Jordan two main sources are available to be desalted: the Aqaba Gulf and the brackish deep groundwater in some basins. Preliminary studies showed that by the year 2010 more than 2×10^7 of brackish water could be developed in central Jordan. This figure may reach 7×10^7 by the year 2040. According to the water quality analysis conducted by the Japanese International Cooperation Agency on brackish water in Jordan, the total dissolved solids results were in the range of 5,000–10,000 ppm [24].

6. Multiobjective analysis

The AHP has been effective in structuring many types of complex multi-criterion problems. For example, it has been applied to business decisions [25], choosing areas of research and development programs [26], the estimate of the economy's impact on sales, the problem of traffic congestion, real estate investment [27], and water policy [28]. The AHP enables decision-makers to structure a problem in the form of a hierarchy of preferences through a series of pairwise comparisons of relevant factors or criteria.

There are five basic steps in applying the AHP in practice [29]: (1) structuring the decision hierarchy, (2) collecting data by pairwise comparisons, (3) checking consistency of material judgments, (4) applying the eigenvector method to compute weights, and (5) aggregating the weights to determine a ranking of decision alternatives. The primary advantage of the basic AHP approach is its simplicity; once the criteria are agreed upon and supporting data collected for each alternative, the AHP analysis can be processed. Sensitivity analysis can be used to test the solution and examine how changes in criterion weights would alter the final weight and ranking of the individual alternatives.

In this paper the problem of choosing the best non-conventional water resource in Jordan is evaluated in terms of economic, technical, availability, reliability and environmental criteria. The problem was structured into three levels as shown in Fig. 3. The first level defines the goal to be achieved, which is the selection of the best non-conventional water resource. The second one defines the criteria and the third shows the four non-conventional water resources available in Jordan. These include treated wastewater (WW), water harvesting (WH), water importation (WI), and desalinated water (DW).

In order to establish the priorities, i.e., weights, of the alternatives, pairwise comparisons were necessary, i.e., to compare the alternatives in pairs against a given criterion (see Fig. 4), which was developed by Saaty [27]. It defines values from 1 to 9 assigned to judgments in comparing pairs of level 3 against a criterion in the second level of the hierarchy. Table 2 shows the relational scoring and relative weights for the different non-conventional water resources considered, while Table 3 presents the relational scoring for all criteria with respect to each other,

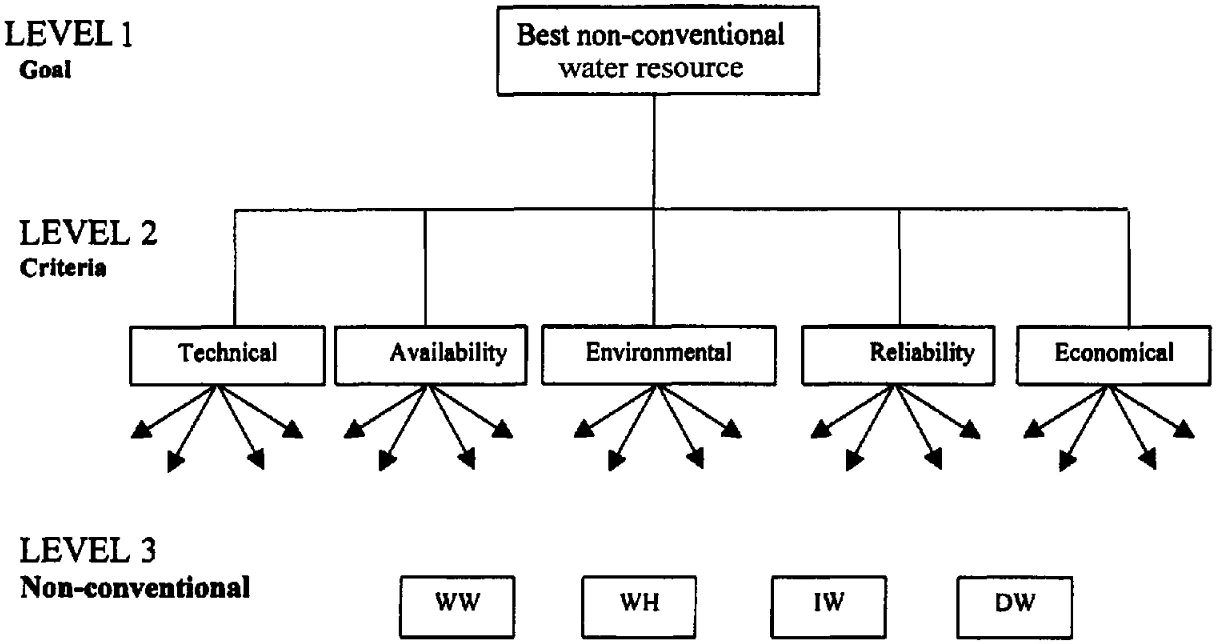

Fig. 3. Three-level hierarchy problem.

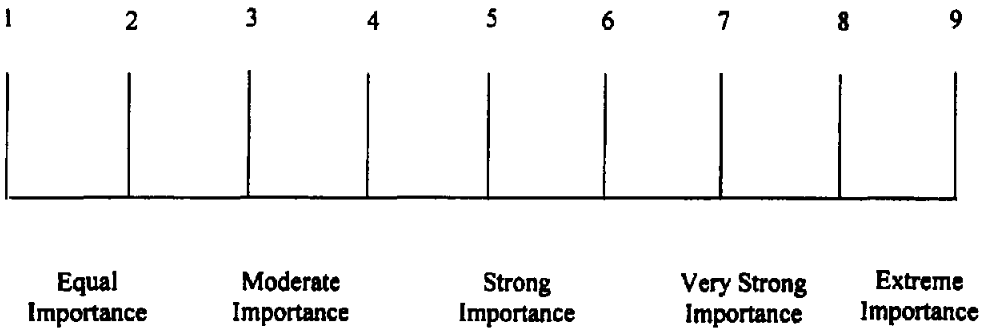

Fig. 4. Pairwise comparison scale.

as well as the relative weight scorings of each criterion. This is the pairwise comparison matrix of the goal defined at level 1: the best non-conventional water resource in Jordan. The last column gives the relative weight of their priorities, which indicates that reliability is the most important, followed by availability, economy, technical and environmental sustainability. All four entries in the vector of priorities obtained in each of the five matrices are weighted by the priority for that corresponding criterion. An overall relative weight factor is then obtained from the results of Tables 2 and 3. These weights are of the overall relative priorities

Table 2
Rational scoring and relative weights of non-conventional water resources

Criteria	WW	WH	WI	WD	Relative weights
Economical:					
WW	1	1/7	3	2	0.17
WH	7	1	8	4	0.62
WI	1/3	1/8	1	1/5	0.05
WD	1/2	1/4	5	1	0.17
Technical:					
WW	1	1/7	1/5	1/3	0.06
WH	7	1	6	2	0.54
WI	5	1/6	1	1/2	0.16
WD	3	1/2	2	1	0.24
Availablity:					
WW	1	1/4	3	1/5	0.11
WH	4	1	8	1/2	0.35
WI	1/4	1/8	1	1/7	0.05
WD	5	2	7	1	0.50
Reliability:					
WW	1	1/7	2	1/8	0.07
WH	7	1	4	1/3	0.28
WI	1/2	1/4	1	1/9	0.06
WD	8	3	9	1	0.59
Environmental:					
WW	1	1/5	1/4	1/3	0.08
WH	5	1	3	2	1.88
WI	4	1/3	1	1/2	0.19
WD	3	1/2	2	1	0.27

Table 3
Rational scoring and relative weights of criteria

Criteria	Economical	Technical	Availability	Reliability	Environmental	Relative weight
Economical	1	2	1/3	1/4	3	0.30
Technical	1/2	1	1/4	1/5	5	0.11
Availability	3	4	1	1	6	0.34
Reliability	4	5	1	1	7	0.39
Environmental	1/3	1/5	1/6	1/7	1	0.05

Table 4
Overall relative weights for optimum non-conventional water resources

	Water sources			
	WW	WH	WI	WD
Economical (0.13)	0.17	0.62	0.05	0.17
Technical (0.11)	0.06	0.54	0.16	0.24
Availability (0.34)	0.11	0.35	0.05	0.50
Reliability (0.39)	0.07	0.28	0.06	0.59
Environmental (0.05)	0.08	1.88	0.19	0.27
Relative weight[a]	0.094	0.435	0.074	0.462

[a]Relative weight is the sum of individual weights after being multiplied by a factor against each criterion.

of the four different non-conventional water resources against the five criteria, as they are presented in Table 4.

7. Results and discussion

Pairwise comparisons were conducted on the components of the hierarchy (Fig. 4) from the upper to lower levels; calibrations of pairwise comparisons are carried out to ensure consistency in judgments.

The rationale for setting priorities and assigning weights was based on comprehensive information on Jordan's water sector, the problems and constraints of water resources, and supply and demand issues. The analyses of the various non-conventional water resources reveal that DW enjoyed the most favorable option under the developed criteria. Relative global weights were generated for the four non-conventional water resources considered (Fig. 5). DW and WH have the highest ranks, with relative weights of 0.462 and 0.435, respectively. WW and WI have much lower values of relative weights, i.e., 0.094 and 0.074, respectively.

Desalinated water in Jordan is likely to be a potential non-conventional water resource in the near future. In a previous paper, Mohsen and

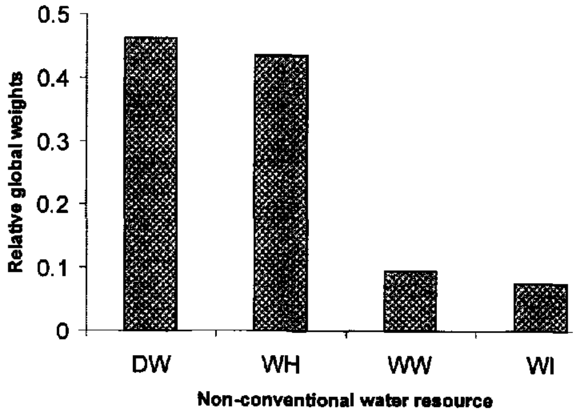

Fig. 5. Relative global weights for the four non-conventional water resources.

Al-Jayyousi [23] showed that utilizing reverse osmosis for desalinating brackish water offers a viable option for Jordan to meet the unsatisfied water demand, especially for large industrial projects such as oil shale development. Seawater desalination has a low weight when compared to brackish water due to the relative cost.

8. Conclusions

There are good prospects for non-conventional water resources, such as the effluents from waste water treatment plants, desalination and water harvesting. Desalination of brackish water offers a potential for water supply enhancement in Jordan. When evaluating various non-conventional water resources available in Jordan, water desalination was ranked the highest. The criteria under which multicriteria analyses were performed were economic, technical, availability, reliability, and environmental sustainability. Further studies and training need to be carried out in the near future in order to promote and enforce the technology transfer in the field of desalina-tion among the interested groups, especially governmental institutions, in Jordan.

9. References

[1] Annual Statistical Report, Department of Statistics, Amman, Jordan, 1998.

[2] National Population Strategy, General Secretariat of National Population Committee, Amman, Jordan, 2000.

[3] O.R. Al-Jayyousi and M.R. Shatanawi, Wat. Res. Develop., 11 (1195) 315.

[4] National Environment Strategy, Ministry of Municipal and Rural Affairs and the Environment, Amman, Jordan, 1992.

[5] National Environment Action Plan, Ministry of Planning, Amman, Jordan, 1996.

[6] A Strategy for Managing Water in the Middle East and North Africa, World Bank, Washington, DC, 1994.

[7] From Scarcity to Security: Averting a Water Crisis in the Middle East and North Africa, Washington, DC, 1995.

[8] E. Salameh, Proc., Symposium on Jordan's Water Resources and Their Future Potential, Amman, Jordan, 1992, pp. 113–120.

[9] M. Murakami, Managing Water for Peace in the Middle East, United Nations University Press, Tokyo, Japan, 1995, pp. 167–201.

[10] M. Ragheb, K. Toukan and R. Al-Weshah, Proc., Int. Symp. on Water Resources in the Middle East: Policy and Institutional Aspects, Urbana, IL, USA, 1993, pp. 173–180.

[11] J.O. Jaber, S.D. Probert and O. Badr, Appl. Energy, 57 (1997) 45.

[12] E. Salameh, Water Quality Degradation in Jordan: Impacts on Environment, Economy and Future Generations Resources Base, Royal Society for the Conservation of Nature, Amman, Jordan, 1996.

[13] Annual Reports, Water Authority, Amman, Jordan, 1996 and 1997.

[14] Annual Report, Water Authority, Amman, Jordan, 1998.

[15] R. Ta'ni, Water Resources and Usage in Jordan, Ministry of Water and Irrigation, Amman, Jordan, 1999.

[16] M. Hadaddin, Address to the students' of Al El-Bait University, Addustour Newspaper, Amman, Jordan, 1997.

[17] Annual Report, Ministry of Energy and Mineral Resources, Amman, Jordan, 1996.

[18] Updating and Revising Environmental Guidelines for Energy Sector Operations in Jordan, Ministry of Energy and Mineral Resources, Amman, Jordan, 1996.

[19] National Water Demand Forecast, Ministry of Water and Irrigation, Amman, Jordan, 1996.

[20] O.R. Al-Jayyousi, Agricultural adjustment systems in the Jordan rift valley, Technical Report, University of Applied Sciences, Amman, Jordan, 1995.

[21] Pride Team Technical Report, A Water Management Study of Jordan, Ministry of Water and Irrigation, Amman, Jordan, 1992.

[22] H.C. Preul, 8th IWRA World Congress on Water Resources, Cairo, Egypt, 1994.

[23] M.S. Mohsen and O.R. Al-Jayyousi, Desalination, 124 (1999) 163.

[24] JICA, Final Report on Brackish Groundwater Desalination in Jordan, Amman, Jordan, 1995.

[25] M. Kabariti and A. Taher, Proc., 4th Arab Int. Solar Energy Conf., Amman, Jordan, 1993, pp. 1023–1033.

[26] F. Elkarmi, Proc., 4th Arab Int. Solar Energy Conf., Amman, Jordan, 1993, pp. 1003–1013.

[27] T.L. Saaty, Decision Making for Leaders: The Analytic Hierarchy Process for Decision Making, RWS, Pittsburgh, PA, 1988.

[28] B.A. Akash, O.R. Al-Jayyousi and M.S. Mohsen, Desalination, 114 (1997) 1.

[29] T.L. Saaty, The Analytic Hierarchy Process, McGraw-Hill International, 1980.