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An Optimization Approach for Multi-Sectoral Water Supply Management in the Greater Beirut Area

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Abstract. This paper presents a model that was developed and applied to serve as a water supply multi-sectoral decision support system for water resources management taking economic and socio-environmental factors into consideration. The applicability of the model was tested in the Greater Beirut Area by examining future supply-demand management alternatives and quantifying the cost-benefit of viable policies. The effect of eliminating a particular source to account for resources depletion and public acceptability, as well as increased returns from water use were proven to affect greatly the water allocation scheme. The model can also be a useful tool to assess the effect of decreasing unit costs from water supply options (desalination) and the resulting breakeven point, and the effect of increased water demand due to unplanned growth (tourism).

Key words: conventional and non-conventional water resources, linear programming, optimization, water allocation

Introduction

While it is contented that Lebanon is one of the countries in the region having abundant water resources, it is commonly accepted that the water sector in Lebanon suffers from technical, management, administrative and institutional constraints limiting safe access to water and creating serious adverse socio-economic impacts (El-Fadel *et al.*, 2002, 2003). Economic development activities, high population growth, over-consumption, urbanization, inefficient supply and irrigation systems, and increased pollution levels are all contributing to the depletion of water resources, and consequent water shortages. In addition, the unsustainable use of water, which has been perceived as abundant and infinite, and the lack of an integrated water policy to manage and conserve available resources and study the viability of alternative ones are major roots to water resources problems (El-Fadel *et al.*, 2003; ESCWA, 1999; Ghannam *et al.*, 1998; Al Hajjar, 2001). These problems are most pronounced in the Greater Beirut Area (GBA) where nearly half the country's population resides.

The objective of the present study is the development of a tool that can help decision-makers in assessing alternative water resources management strategies and obtain the optimal combination of water supply options that meets projected water demands in an economic and environmentally sustainable way. For this purpose, a water resources allocation model was developed and applied to serve as a multi-sectoral decision support system for water resources management in the GBA. The model accounts for water supply rates from various water supply sources, water demand rates for competing sectors, water cost and charges associated with supplies and demand sectors including transmission distance. It uses a linear programming formulation with the framework of dynamic optimization to determine the optimal water allocation pattern. The applicability of the model was tested in the GBA by examining future supply-demand management alternatives and quantifying the cost-benefit of viable policies. The effect of eliminating certain water supply sources to account for resource depletion and public acceptability, as well as increased returns from water use were examined alongside with the effect of decreasing unit costs from water supply options (desalination) and the resulting breakeven point, and the effect of increased water demand due to unplanned growth (tourism).

Study Area Characterization

The study area encompasses the city of Beirut and its suburbs with a population exceeding 1.5 M living in an area of about 253 km^2 located at elevations ranging from 0 to 400 m above mean sea level (Figure 1). Table I summarizes the total water supply capacities for the area with and without future proposed expansions.

Water demand in the GBA is shared between four principal sectors, namely domestic, industry, agriculture and tourism, as outlined in Table II which summarizes the sectoral and total water demand for the GBA including the losses in the network. Evidently, in the absence of an effective water allocation policy, the gap between water demand and supply will widen in future years.

Several alternatives have been proposed to meet the projected water demand and avoid the expected shortage in the GBA, including the expansion of existing surface and groundwater resources[1] as well as relying on non-conventional alternatives such as wastewater reclamation,[2] seawater desalination,[3] and rainwater harvesting.[4] Estimates for the daily available potential water supply for these sources are summarized in Table III.

The unit cost estimates of water from the various water supply options are summarized in Table IV. These costs include construction, operation and maintenance, and transmission costs. Social and environmental costs were not directly internalized into these costs due to data limitations. Note that the unit cost of water is a function of many variables, including but not limited to the water supply source, the sector to which it will be supplied or end use, the technology used, the capacity installed, the land availability, and the initial water quality or level of treatment required.

The current water charging system levies a non-volumetric flat-rate tariff that is independent of the level of water use. In addition, the current charging scheme does

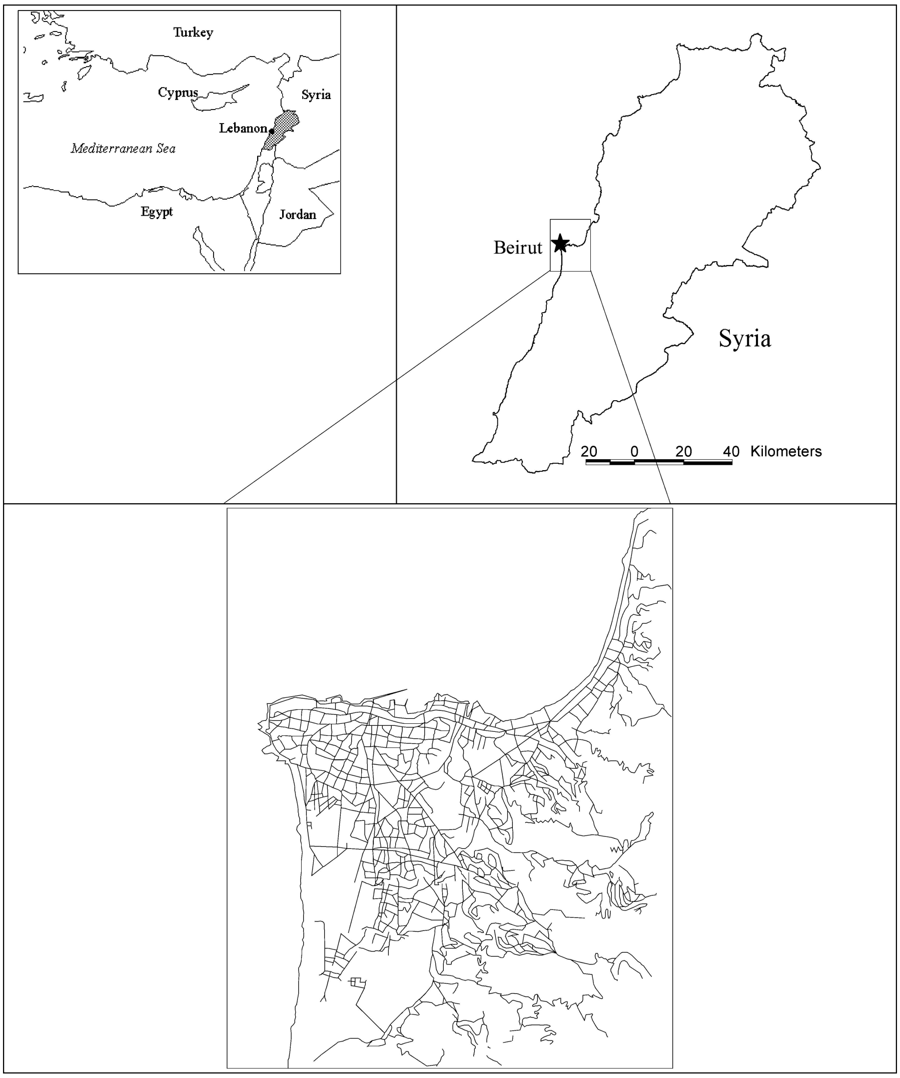

Figure 1. Study area.

not differentiate between domestic, commercial, industrial, or touristic demands in terms of water tariffs (WB, 2001; Al Hajjar, 1997), but it does with respect to the agricultural sector. Charges to the various sectors are presented in Table V.

Model Formulation

Water has traditionally been provided to meet demand with significant involvement of the government. Allocation by governments, usually referred to as public allocation, has usually not addressed economic efficiency. However, appropriate

Table I. Total water supply capacities for the GBA (Modified after Yamout, 2002)

Source	Local nomenclature	Flow (m^3/day)	
		Wet	Dry
Surface water	El Kalb river		
	Current	250,000	104,000
	Future	500,000	104,000
	Beirut river		
	Current	30,000	20,000
	Future	73,000	29,000
Groundwater	Various wells		
	Current	110,000	140,000
	Future	110,000	187,000
Total	Current	390,000	164,000
	Future	647,000	320,000

Table II. Seasonal sectoral water demand of the GBA

	Sector (m^3/day)						
	Domestic	Industry	Agriculture		Tourism	Total	
Year	Wet and dry	Wet and dry	Wet	Dry	Wet and dry	Wet	Dry
2000	427,500	211,818	0	136,739	6,209	645,527	782,265
2010	455,625	363,574	0	90,751	12,428	831,627	922,378
2020	471,600	421,663	0	59,486	21,287	914,550	974,036
2030	540,000	554,020	0	43,867	35,686	1,129,705	1,173,572

Note. Although the agricultural water demand in Lebanon is projected to increase from 870 MCM/year to 1600 MCM/year (El-Fadel *et al.*, 2000), the agricultural water demand for the GBA is anticipated to decrease due to expected demographic and industrial expansion in this area.

Table III. Available potential supply for the GBA (Modified after Yamout, 2002)

	Source of supply ('000 m^3/day)					
	Conventional sources		Non-conventional sources			
	Awali river phase 1	Awali river phase 2	Rainwater harvesting		Wastewater reclamation	Seawater desalination
Year	Wet and dry	Wet and dry	Wet	Dry	Wet and dry	Wet and dry
2000	260	520	243	0	280	No limit
2010	260	520	243	0	400	No limit
2020	260	520	243	0	495	No limit
2030	260	520	243	0	612	No limit

Table IV. Cost of supplying water to the GBA from water supply options to water demand sectors[a]

	Sector (j) ($/m^3)			
Source (i)	Domestic (1)	Industry (2)	Agriculture[j] (3)	Tourism (4)
Groundwater wells (1)	0.13	0.13	0.13	0.13
Awali river (phase 1)[b] (2)	0.33	0.33	0.13	0.33
Awali river (phase 2)[c] (3)	0.42	0.42	0.28	0.42
Beirut river[d] (4)	0.10	0.10	0.06	0.10
El Kalb river[e] (5)	0.12	0.12	0.06	0.12
Rainwater harvesting (6)	3.06[f]	3.06[f]	0.60[g]	3.06[f]
Wastewater reclamation[h] (7)	0.92	1.41	0.42	0.92
Seawater desalination[i] (8)	0.60	0.60	0.60	0.60

[a]Note that, unless stated otherwise, costs are based on estimates by GIBB-KA-KCIC for the Council for Development and Reconstruction (CDR) and the Ministry of Energy and Water (MEW) in a financial analysis study carried out for all water and wastewater projects designed for the Greater Beirut Area in 1997.
[b]Ouardaniye Water Treatment Plant (phase 1) and Beirut Awali Water Conveyor (phase 1).
[c]Ouardaniye Water Treatment Plant (phase 2), Beirut Awali Water Conveyor (phase 2), and Bisri dam.
[d]Chaabouni (2001); cost estimates cover water pumping and treatment (Ain El Delbe Water Treatment Plant).
[e]Dbaye Water Treatment Plant and El Kalb Water Conveyor.
[f]Roof systems: UNEP (1997).
[g]Nimeh (2001); cost estimates include hill lake construction and water transmission cost through Beirut Awali Water Conveyor (phase 1).
[h]Adopted from Asano (1998) (capacity $\geq$ 40,000 m^3/day).
[i]Adopted from Morin (1999) (capacity $\geq$ 30,000 m^3/day).
[j]Treatment is not required for agricultural use.

Table V. Current sectoral water charges in the GBA

Sector (j)	Tariff ($/m^3)
Domestic (1)	0.42[a]
Industry (2)	0.42
Agriculture (3)	
Pumping	0.02[b]
Gravity	0.01[b]
Drip	0.02[b]
Tourism (4)	0.42

[a]As charged by Beirut Water Authority, BWA (Al Hajjar, 1997).
[b]As charged by Litani River Authority, LRA (Awaida, 2000).

means of resource allocation are necessary to achieve optimal usage of the resource (Dinar *et al.*, 1997). In this context, an optimization model was developed using a linear programming (LP) approach that may be relied on in planning the water supply scheme for the area.

The general problem that will be addressed in the model can be described as follows: given the rates of available water from different water supply options, the rate of water demand by competing sectors, the relative location of supply sources and demand sectors, and the cost structure (economic and environmental), determine how water should be allocated so that the overall cost (economic and environmental) of the system is minimized. The model can be further used to explore the sensitivity of the water allocation system to various operational parameters, and to predict the outcome of possible policy changes so that alternative management schemes may be evaluated. The formulation of the model provides a wide range of applications. Depending on data availability and the required level of detail, model terms can be modified to provide an optimum path for every scenario. The mathematical formulation of the LP model with the frame of dynamic optimization is described below.

DECISION VARIABLES

The model decision variables are the amount of water, Q, to be allocated from each source to each sector. For simplicity, they are denoted Q_{ij}, where i and j designate the supply source and the sector, respectively (Figure 2). The number of variables that are accounted for when solving the model equations vary with each scenario. Note that the available water amount is a function of the supply source, the season and the development scale. Although water amounts vary from season to season and year to year depending on climatologic conditions, the water supply sources are assumed to have a constant wet-season flow for the purpose of simplicity and

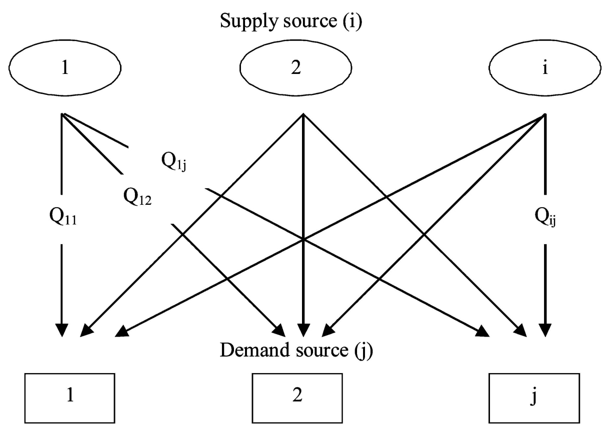

Figure 2. Schematic presentation of the model variables.

can be modified as desired. Surface- and groundwater availability based on wet season flows were used for this analysis because of their dominance in Lebanon's annual water balance.

OBJECTIVE FUNCTION

The objective function of scenarios A through C of the model is a net return (NR) maximization function. It can be expressed by Equation (1) which considers the maximization of the difference between the revenues of supplying water to each sector (*j*) from each water supply source (*i*) and the amortized costs of doing so (Equations (1a) and (1b)). The discount factor depreciates future costs relative to present costs according to the interest rate; it is set to unity ($\beta_t = 1$) in the model application as the cost in Table IV are already discounted estimates. The problem can also be addressed as a cost (*C*) minimization function by reducing the objective function to Equations (1c).

$$\text{MAXNR} = \sum_{i=1}^{m}\sum_{j=1}^{n} \text{NR}_{ij} \tag{1}$$

$$\text{MAXNR} = \sum_{i=1}^{m}\sum_{j=1}^{n} [(R_{ij} \times Q_{ij}) - \beta_t(C_{ij} \times Q_{ij})] \tag{1a}$$

$$\beta_t = \frac{1}{(1+r)^t} \tag{1b}$$

$$\text{MINC} = \sum_{i=1}^{m}\sum_{j=1}^{n} [\beta_t(C_{ij} \times Q_{ij})] \tag{1c}$$

where Q_{ij} is the amount of water allocated from source *i* to sector *j*, C_{ij} the cost associated with supplying water from source *i* to sector *j*, R_{ij} the return associated with supplying water from source *i* to sector *j*, *m* the number of sources, *n* the number of sectors, β_t the discount factor, *r* the interest rate, *t* the time interval considered.

The cost of water supply, C_{ij}, consists of two major categories: economic, (C_{ij}^{E}), and socio-environmental, (C_{ij}^{SE}) (Equation (2a)). The economic cost component includes construction cost (C_{ij}^{C}), operation and maintenance costs ($C_{ij}^{\text{O\&M}}$), and transmission cost (C_{ij}^{T}) of water from the source to the end user (Equation (2b)).

$$C_{ij} = C_{ij}^{\text{E}} + C_{ij}^{\text{SE}} \tag{2a}$$

$$C_{ij}^{\text{E}} = C_{ij}^{\text{C}} + C_{ij}^{\text{O\&M}} + C_{ij}^{\text{T}} \tag{2b}$$

The socio-environmental component, (C_{ij}^{SE}), is incorporated as a method to internalize the environmental and social impacts costs into the costs of the water supply. This cost is mainly a function of the water supply option considered. However, most socio-environmental impacts associated with each supply source are difficult to quantify in monetary terms and there is no one standard method applied in their valuation.

The unit return from water supply, R_{ij}, is a function of the sector to which this water is allocated and the policy adopted by the country in its regard.

CONSTRAINTS

The objective function is subject to four constraints, namely total water availability,[5] water demands,[6] policy requirements,[7] and non-negativity which are expressed in Equations (3)–(5). The general optimization model formulation, which sets supply greater than or equal to demand is represented below. In the specific case of this optimization, excess supply holds no utility. Supply has therefore been equated to demand in all model scenarios.

$$\sum_{j=1}^{n} Q_{ij} \leq Q_i \text{ Available} \tag{3}$$

$$\sum_{i=1}^{m} Q_{ij} \geq Q_j \text{ Demand} \tag{4}$$

$$Q_{ij} \geq 0 \tag{5}$$

Scenario Definition

The selected model parameters and their level of details and accuracy directly affect the reliability of the model's output. The model parameters that need determination are the water supply sources and demand sectors and their associated costs and revenues. The water supply alternatives including the existing and proposed conventional resources, consist of (1) groundwater wells, (2) conveyance from Awali River (Awali phase 1), (3) conveyance from Awali River after the construction of Bisri Dam (Awali phase 2), (4) abstraction from Beirut River springs, and (5) conveyance from El Kalb River. The model also includes other non-conventional sources, namely, (6) rainwater harvesting, (7) wastewater reclamation, (8) and seawater desalination, to assess the economic and socio-environmental viability of these options, as compared to conventional sources. On the other hand, the water demand sectors are (1) domestic, (2) industry, (3) agriculture, and (4) tourism where the model variables are the amount of water that should be allocated from each existing and future water supply source to each of the water demand sectors of the GBA. This resulted in a problem of 32 decision variables (Table VI) and 14 constraints. The model constants are the estimates made for the sectoral water demand, the water availability of the various sources considered, and the costs and charges of water associated with all source/sector combinations.

Table VI. Model decision variables

	Definition			
Designation, Q_{ij}	i	Source	j	Sector
Q_{11}	1	Groundwater wells	1	Domestic
Q_{12}			2	Industry
Q_{13}			3	Agriculture
Q_{14}			4	Tourism
Q_{21}	2	Awali phase 1	1	Domestic
Q_{22}			2	Industry
Q_{23}			3	Agriculture
Q_{24}			4	Tourism
Q_{31}	3	Awali phase 2	1	Domestic
Q_{32}			2	Industry
Q_{33}			3	Agriculture
Q_{34}			4	Tourism
Q_{41}	4	Nahr Beirut River	1	Domestic
Q_{42}			2	Industry
Q_{43}			3	Agriculture
Q_{44}			4	Tourism
Q_{51}	5	Nahr El Kalb River	1	Domestic
Q_{52}			2	Industry
Q_{53}			3	Agriculture
Q_{54}			4	Tourism
Q_{61}	6	Rainwater harvesting roof systems	1	Domestic
Q_{62}			2	Industry
Q_{63}			3	Agriculture
Q_{64}			4	Tourism
Q_{71}	7	Wastewater reclamation	1	Domestic
Q_{72}			2	Industry
Q_{73}			3	Agriculture
Q_{74}			4	Tourism
Q_{81}	8	Seawater desalination	1	Domestic
Q_{82}			2	Industry
Q_{83}			3	Agriculture
Q_{84}			4	Tourism

Eight basic scenarios (A–H) were examined to determine the optimal multi-sectoral allocation pattern (Table VII). For each scenario eight simulations (1–8) were conducted to cover the wet and dry seasons of the years 2000, 2010, 2020, and 2030.

Table VII. Simulated scenarios and sub-scenarios

Scenario	Description
Net return maximization: scenarios A–C	
A	No restrictions are applied
B	Socio-environmental policy constraints are applied
	Groundwater resources were given a maximum capacity of zero
	Wastewater reclamation was excluded as a water supply alternative for domestic, industrial, and touristic purposes
	Rainwater harvesting was not included as a water supply alternative for domestic purposes
	Seawater desalination was not included as a water supply alternative for agricultural purposes
C	Apply socio-environmental policy constraints (refer to B)
	Apply restrictions on water charges which were set as a percent of the cost of supplying water from the different sources
	Domestic: 110%
	Agricultural: 110%
	Industrial: 150%
	Touristic: 200%
Total cost minimization: scenarios D–H	
D	Apply socio-environmental policy constraints (refer to B)
	Water charges are set at zero
E	Apply socio-environmental policy constraints (refer to B)
	Water charges are set at zero
	Cost of saltwater desalination is decreased to at \$0.45/m^3
F	Apply socio-environmental policy constraints (refer to B)
	Water charges are set at zero
	Cost of saltwater desalination is decreased to at \$0.30/m^3
G	Apply socio-environmental policy constraints (refer to B)
	Water charges are set at zero
	Cost of saltwater desalination is decreased to at \$0.15/m^3
H	Apply socio-environmental policy constraints (refer to B)
	Water charges are set at zero
	Number of tourists is three times that estimated and used in all other scenarios, with a stay period of 15 days; these tourists reside and spend the majority of their time in the GBA and are present mainly during the summer season (July through September), which is equivalent to 90 days. The peak number of tourists is reached by the year 2020 (Yamout, 2002).

Year	Projected arrivals	Projected demand (m^3/day)
2000	2,546,139	212,178
2010	5,663,085	471,924
2020	10,912,287	909,357
2030	10,912,287	909,357

The first *base scenario A* includes all the water supply sources suggested and all the water demand sectors, using current estimated costs and charging schemes.

Since *social and environmental* concerns were not assigned explicit monetary values, the second *scenario B* attempts to analyze the optimal pattern of water allocation while accounting for *social and environmental* concerns. These concerns are resource depletion, public acceptability, and user ability to pay. To account for them respectively, (1) groundwater resources are conserved for emergency use only, (2) wastewater reclamation was excluded as a water supply alternative for domestic, industrial, and touristic purposes, (3) rainwater harvesting and seawater desalination were not included as water supply alternatives for domestic and agricultural water supply, respectively, due to their hindering cost.

The purpose of *scenario C* is to determine the optimal water allocation and net revenue in the case the charges are set equal or greater than the cost of water to insure excess revenues that allow the public sector to maintain and/or expand the water supply system. This scenario includes the assumptions made under *scenario B*.

Whether the issue of water allocation should be treated as a *net return maximization* problem or a total *cost minimization* problem is a matter of continuous debate. While scenarios A–C, allocated water through the first approach, scenarios D–H used the second one. As such, the model was run using unit returns from water allocation of zero from all sectors. The objective function is a net cost minimization function. Note that these scenarios are based on *scenario B*.

Scenarios D–G assess the decrease in unit cost of a water supply option, *desalination*, and its effect on the water allocation scheme. The costs of desalination used ranged from a high of 0.60 $/m^3 (D) to a low of 0.15 $/m^3 (G). The cost is decreased by increment of 0.15 resulting in two additional scenarios: E (0.45 $/m^3) and F (0.30 $/m^3).

Scenario H assesses future conditions associated with significant *tourism growth*. Tourism is proving itself as a sector that is exponentially growing in the area, as it was witnessed in the summer of 2002 and 2003, whereby the number of tourists and the stay period exceeded by far earlier predictions.

Results and Discussion

Table VIII presents the net returns from a certain source and sector and their corresponding percentage return from the total net return. Note that a negative net return (or percentage) indicates a loss figure. In addition, an increase in water demand does not necessarily generate an increase in return, specifically when this increase is accompanied by a shift in supply to a more expensive source.

For the *base scenario A*, four conventional water supply sources can be used (El-Kalb River, Awali phase I, Groundwater wells, and Beirut River) to satisfy the water demand in an optimal way. The contribution of non-conventional water resources to the water supply (through seawater desalination) is insignificant (1% in year 2020). The total net return from water allocation increases with the total water

Table VIII. Simulation results under conditions of scenarios A–D

Sector			Domestic		Industrial		Agriculture		Tourism	
Scenario	Year	Source	%	$	%	$	%	$	%	$
(A) Base scenario	2010	Groundwater	14.87	11.64	0	0	0	0	0	0
		Awali I	0	0	6.25	4.89	−1.94	−1.52	0	0
		Awali II	0	0	0	0	0	0	0	0
		Beirut river	0	0	10.89	8.53	0	0	0	0
		ElKalb river	48.39	37.89	19.86	15.55	0	0	1.68	1.31
		Rain harvest	0	0	0	0	0	0	0	0
		WW reuse	0	0	0	0	0	0	0	0
		Desalination	0	0	0	0	0	0	0	0
	2020	Groundwater	14.50	11.64	0	0	0	0	0	0
		Awali I	0	0	8.46	6.79	−1.23	−0.99	0.50	0
		Awali II	0	0	0	0	0	0	0	0
		Beirut river	0	0	10.62	8.53	0	0	0	0
		ElKalb river	48.81	39.18	19.39	15.57	0	0	0	0
		Rain harvest	0	0	0	0	0	0	0	0
		WW reuse	0	0	0	0	0	0	0	0
		Desalination	−0.34	0	0	0	0	0	−0.72	−0.57
	2030	Groundwater	15.91	11.64	0	0	0	0	0	0
		Awali I	0	0	0	0	0	0	0	0
		Awali II	0	0	0	0	−2.38	−1.74	0	0
		Beirut river	0	0	11.65	8.53	0	0	0	0
		ElKalb river	64.34	47.09	10.47	7.67	0	0	0	0
		Rain harvest	0	0	0	0	0	0	0	0
		WW reuse	0	0	0	0	0	0	0	0
		Desalination	0	0	0	0	0	0	0	0
(B) Socio-environmental policy constraints	2010	Groundwater	0	0	0	0	0	0	0	0
		Awali I	0	0	10.93	7.28	−2.29	−1.52	0	0
		Awali II	0	0	0	0	0	0	0	0
		Beirut river	0	0	12.81	8.53	0	0	0	0
		ElKalb river	68.84	45.83	11.43	7.61	0	0	1.97	1.31
		Rain harvest	0	0	0	0	0	0	0	0
		WW reuse	0	0	0	0	0	0	0	0
		Desalination	−3.70	−2.46	0	0	0	0	0	0
	2020	Groundwater	0	0	0	0	0	0	0	0
		Awali I	0	0	12.27	7.73	−1.57	−0.99	0	0
		Awali II	0	0	0	0	0	0	0	0
		Beirut river	0	0	13.53	8.53	0	0	0	0

(*Continued on next page*)

Table VIII. (*Continued*)

Sector			Domestic		Industrial		Agriculture		Tourism	
Scenario	Year	Source	%	$	%	$	%	$	%	$
		ElKalb river	82.01	51.68	4.87	3.07	0	0	0	0
		Rain harvest	0	0	0	0	0	0	0	0
		WW reuse	0	0	0	0	0	0	0	0
		Desalination	0	0	−8.92	−5.62	0	0	−2.19	−1.38
	2030	Groundwater	0	0	0	0	0	0	0	0
		Awali I	0	0	0	0	0	0	0	0
		Awali II	0	0	0	0	0	0	0	0
		Beirut river	0	0	14.66	8.53	0	0	0	0
		ElKalb river	94.12	54.75	0.00	0	0	0	0	0
		Rain harvest	0	0	0	0	0	0	0	0
		WW reuse	0	0	0	0	−4.6	−2.68	0	0
		Desalination	0	0	−4.18	−2.43	0	0	0	0
(C) Economic policy constraints	2010	Groundwater	0	0	0	0	0	0	0	0
		Awali I	0	0	0	0	0	0	0	0
		Awali II	0	0	0	0	0	0	0	0
		Beirut river	0	0	0	0	0	0	0	0
		ElKalb river	0	0	0	0	0	0	0	0
		Rain harvest	0	0	62.81	75.25	0	0	6.53	8
		WW reuse	0	0	0	0	0	0.55	0	0
		Desalination	8.34	9.99	20.95	25.10	0	0	0.91	1.10
	2020	Groundwater	0	0	0	0	0	0	0	0
		Awali I	0	0	0	0	0	0	0	0
		Awali II	0	0	0	0	0	0	0	0
		Beirut river	0	0	0	0	0	0	0	0
		ElKalb river	0	0	0	0	0	0	0	0
		Rain harvest	0	0	55.36	72.32	0	0	10.47	13.68
		WW reuse	0	0	0	0	0	0	0	0
		Desalination	7.91	10.34	24.52	32.03	0	0	1.47	1.92
	2030	Groundwater	0	0	0	0	0	0	0	0
		Awali I	0	0	0	0	0	0	0	0
		Awali II	0	0	0	0	0	0	0	0
		Beirut river	0	0	0	0	0	0	0	0
		ElKalb river	0	0	0	0	0	0	0	0
		Rain harvest	0	0	43.87	67.43	0	0	15.26	23.45
		WW reuse	0	0	0	0	0	0	0	0
		Desalination	7.69	11.83	30.86	47.44	0	0	2.14	3.29

(*Continued on next page*)

Table VIII. (*Continued*)

Sector			Domestic		Industrial		Agriculture		Tourism	
Scenario	Year	Source	%	$	%	$	%	$	%	$
(D) *Cost* minimization function	2010	Groundwater	0	0	0	0	0	0	0	0
		Awali I	28.33	17.35	13.85	8.48	2.94	1.80	1.38	0.84
		Awali II	0	0	0	0	0	0	0	0
		Beirut river	2.54	1.55	1.81	1.11	0	0	0	0
		ElKalb river	19.26	11.80	16.49	10.10	0	0	0	0
		Rain harvest	0	0	0	0	0	0	0	0
		WW reuse	0	0	0	0	0	0	0	0
		Desalination	0	0	11.62	7.12	0	0	1.79	1.10
	2020	Groundwater	0	0	0	0	0	0	0	0
		Awali I	23.59	18.27	13.03	10.09	1.51	1.17	0	0
		Awali II	0	0	0	0	0	0	0	0
		Beirut river	2.01	1.55	1.43	1.11	0	0	0	0
		ElKalb river	15.71	12.17	12.57	9.73	0	0	0	0
		Rain harvest	0	0	0	0	0	0	0	0
		WW reuse	0	0	0	0	0	0	0	0
		Desalination	0	0	24.21	18.74	0	0	5.94	4.60
	2030	Groundwater	0	0	0	0	0	0	0	0
		Awali I	0	0	0	0	0	0	0	0
		Awali II	65.09	74.98	4.11	4.74	0	0	0	0
		Beirut river	1.35	1.55	0.96	1.11	0	0	0	0
		ElKalb river	0.00	0	18.71	21.55	0	0	0	0
		Rain harvest	0	0	0	0	0	0	0	0
		WW reuse	0	0	0	0	2	2.81	0	0
		Desalination	1.58	1.83	0	0	0	0	5.34	6.15

% = percent contribution to total annual revenue from all supplies to all sectors.
$ = net return in millions of dollars per year.

demand until the year 2020 then decreases afterwards This decrease is attributed to the decrease in return from the industrial sector by almost half during the period 2020–2030. This is explained as follows. Although the industrial water demand is increasing during this period, this demand is satisfied by a shift to Awali phase 2, a more expensive source of supply. The major contributing sector to the total net return is the domestic sector, followed by the industrial, touristic, and agricultural sectors, for all simulated years. The net return from agriculture is negative for all simulated years due to the relatively low water charge levied on this sector. Similarly, the net return from tourism is negligible due to the low demand and becomes negative in 2020 when desalination contributes to its supply, due to the relatively more expensive cost of this supply option.

When *socio-economic constraints – scenario B –* are imposed, non-conventional water resources can be used with desalination starting 2010 to compensate for excluding groundwater wells as a water supply option while wastewater reclamation can be used starting 2030. The contribution of these non-conventional resources is still less than 10% of the total supply. The contributions of El Kalb River and Beirut River to the total water supply are identical to those of the *base scenario A*. The Awali phase 1 contribution is slightly higher than that of *base scenario A* to compensate for excluding groundwater wells as a supply option. Awali phase 2 replaces Awali phase 1 by the year 2030 with a contribution of 43% of the total supply. Similar to the *base scenario A*, the total net return from water allocation increases with the total water demand until the year 2010 then decreases afterwards due to the decrease in return from the industrial sector by nearly 74% during the period 2010–2030. This is explained by the fact that although the industrial water demand is increasing during this period, this demand is satisfied by a shift to desalination in 2020 and Awali phase 2 in 2030, both of which are relatively more costly sources of supply. For all the simulated years, the major contributor to the total net return is the domestic sector, followed by the industrial, touristic, and agricultural sectors. The net return from agriculture remains negative particularly when wastewater reclamation is introduced because of the relatively higher cost of this supply in comparison to Awali phase 1. Similar to the *base scenario A*, low demand keeps the net return from tourism negligible which becomes negative in 2020 when desalination contributes to its supply, due to the relatively high cost of this supply option.

Under *economic policy constraints – scenario C*, non-conventional water resources can be used immediately to satisfy the water demand in an optimal way. Awali phase 2 is the only conventional water source to contribute (8%) to the total present water demand. As the costs of water from the non-conventional water supply options are higher than those of conventional ones, the resulting net returns are greater than scenarios A and B. Similarly, the total net return from water allocation increases with the total water demand. For all the simulated years, the major contributing sector to the total net return is the industrial sector, followed by far by the domestic, touristic, and agricultural sectors. The net return from agriculture, though decreasing due to the decrease in agricultural water demand, becomes positive because its charge was set higher than its actual cost.

Once a *cost optimization function – scenario D* – is adopted, of El Kalb River supplies a major share (70–43%, years 2000–2030) of the total water supply. Desalination contributes 4, 11, and 3% in the years 2010–2030, respectively. Wastewater reclamation contribution is marginal starting 2030 (2%). Since the net return is the difference between revenues and costs, the cost optimization function translates into similar results as the net return maximization function. Evidently, the total net cost from water allocation increases with the total water demand and thus the major contributor to the total net cost remains the domestic sector followed by the industrial sector, except for the year 2020, when this trend is reversed. The net cost of the touristic and agricultural sectors is negligible due to their comparatively low demands.

The introduction of *desalination – scenarios* (D–G) – showed that allocated water from groundwater wells, El Kalb River, Beirut River, and rainwater harvesting

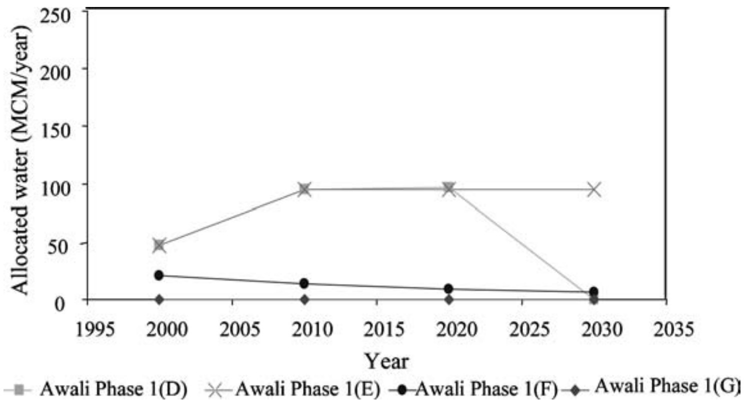

Figure 3. Comparison of total water allocated by Awali phase 1 under conditions of scenarios D–G.

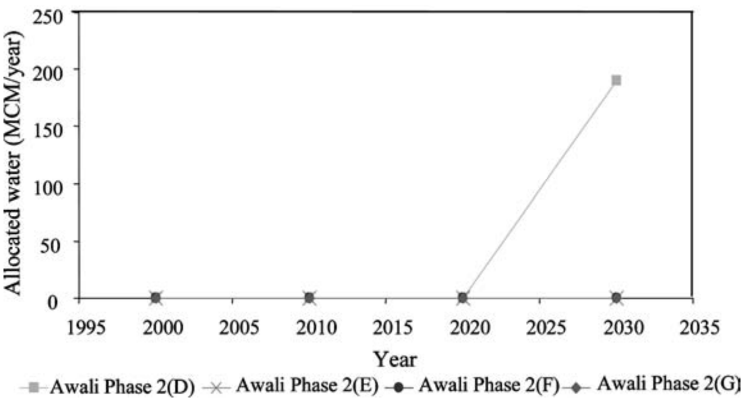

Figure 4. Comparison of total water allocated by Awali phase 2 under conditions of scenarios D–G.

remained the same. The effect of decreasing the cost of desalination was manifested, however, by a variation in the allocated water from three water supply sources: Awali phase 1 and 2, and naturally, desalinated seawater. Figures 3–5 compare the resulting water allocation pattern whereby the amount of water from Awali phase 1 and 2 present a decreasing trend as the unit cost from desalination is decreased, which translates into an increase in the amount of water allocated from seawater resulting in a decrease in total cost from water allocation (Figure 6). These results are further discerned in Figure 7 (a–d) where the total allocated water is depicted as a function of the varying unit cost of desalination for all simulated years. The breakeven point is where the unit costs of seawater desalination at which the amount of water allocated from this option intersects with that allocated from other options, Awali phase 1 and 2. Note that since Awali phase 2 contributes only in the year 2030 of scenario D, it does not intersect with seawater desalination at any unit cost

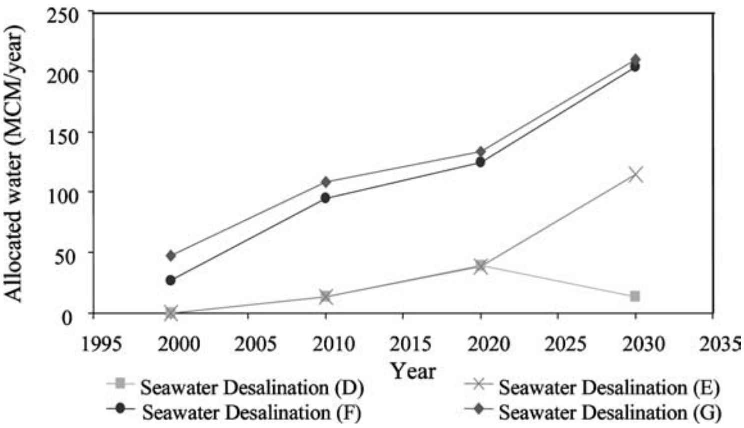

Figure 5. Comparison of total water allocated by seawater desalination under conditions of scenarios D-G.

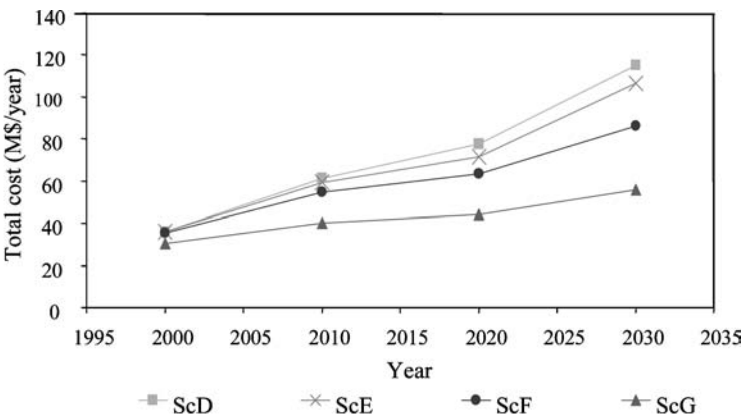

Figure 6. Comparison of total cost from water use under conditions of scenarios D–G.

in the years 2010 and 2020. The same is the case for Awali phase 1 for the year 2030. The breakeven point with Awali phase 1 and 2 ranges from 0.32–0.38 $/m^3$ and 0.45–0.52 $/m^3$, respectively.

Tourism growth – scenario H – indicates that the present contribution of El Kalb River can reach 64% of the total water supply but decreases to 34% by the year 2030 (compared to 70–43 for Scenario D). Desalination can be initiated immediately with an 8% contribution increasing to 25% by the year 2030. Wastewater reclamation can be used starting 2010 at about 4% but this contribution decreases to 1% by the year 2030. Similarly, the contribution of Beirut River decreases from 9 to 5% from the present to 2030 (compared to 11–6% for *base scenario* D). Awali phase 1 can contribute 19% at present until it is replaced by Awali phase 2 at a contribution ranging from 31 to 35% (Figure 8). Clearly, as tourism demand

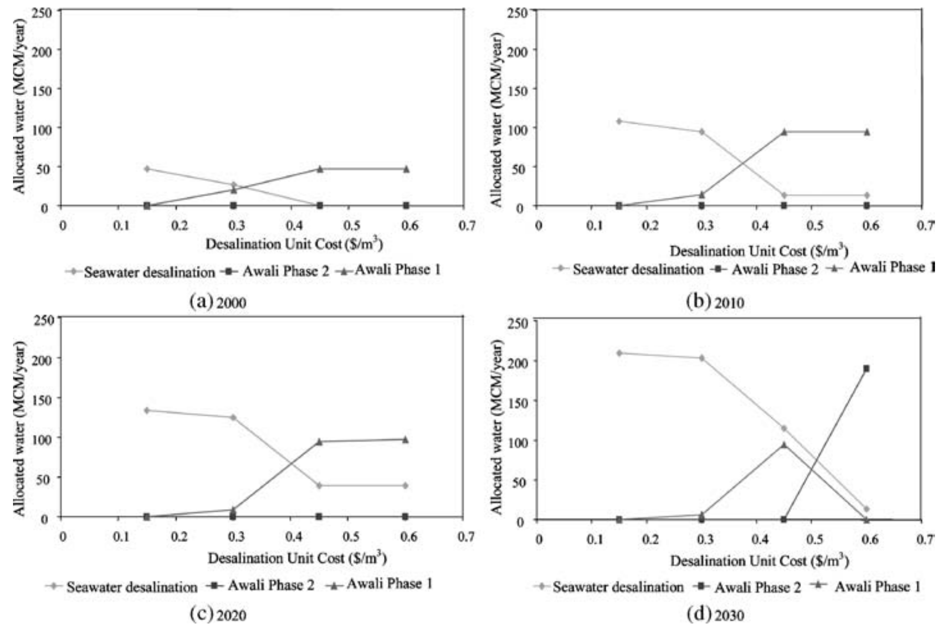

Figure 7. Comparison of total water allocated by Awali phase 1, Awali phase 2, and seawater desalination under different desalination unit costs for the years (a) 2000, (b) 2010, (c) 2020, and (d) 2030.

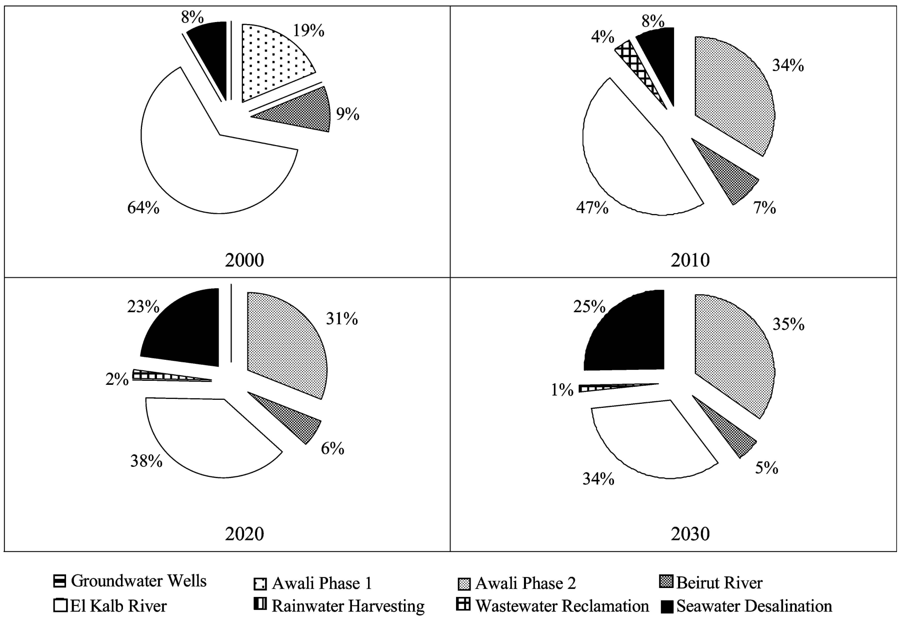

Figure 8. Water supply sources and their respective percentages of the total water supply for the years 2000, 2010, 2020, and 2030 (scenario H).

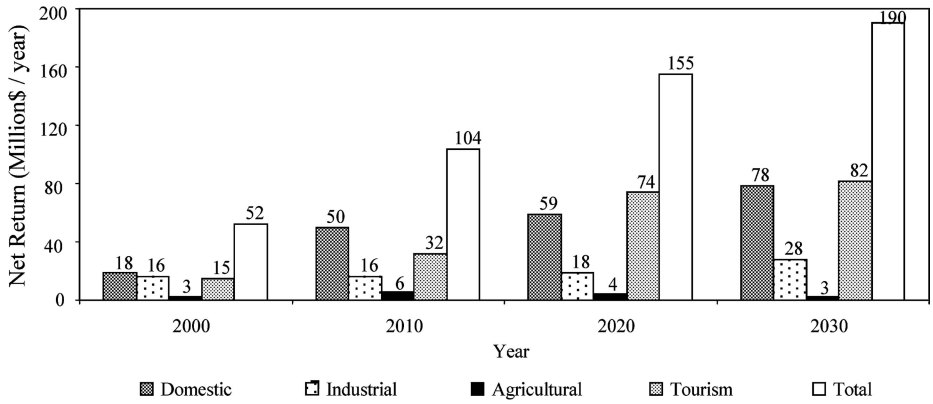

Figure 9. Comparison of net returns from water use under conditions of scenario H.

increases, the optimal water allocation is obtained through the sooner introduction of Awali phase 2 and the sooner and greater use of non-conventional water resources, in comparison to the *base scenario* D. Naturally, the total net cost from water allocation increases with the total water demand, resulting in an increase in the net total cost of water allocation from 52 to 190 million $/year between the years 2000 and 2030, compared to lower values (36–119) for the *base scenario* D. For all simulated years, the major contributor to the total net cost remains the domestic sector followed by tourism unlike all other scenarios, during which the second contributor is the industrial sector. The contribution of the agricultural sector to the net cost also remains negligible due to its comparatively low demand (Figure 9).

Conclusion

A regional LP model was developed to assist decision makers in the planning and setting policies for optimal water resources allocation taking economic, environmental, and social implications into consideration. The model was applied in the Greater Beirut Area to determine the multi-sectoral water allocation pattern that provides the highest net return above water use while fulfilling the main constraints of water availability, seasonal per capita water requirements, as well as other objectives. Comparison of results from various scenarios show that the optimal net return from water use and the corresponding optimal water allocation between the different sectors vary considerably with these objectives (Table IX). In the absence of constraints on the use of the available water supply sources (*base scenario A*), the optimal water allocation relies on conventional water resources. However, when *socio-environmental policy* considerations are introduced (*scenario B*), the optimal water allocation necessitates the use of seawater desalination and wastewater reclamation. When the *charging scheme* is modified to allow for more return from the water supply sector, along with socio-environmental constraints, (*scenario C*),

Table IX. Comparison of net returns/costs (million \$/year) from water use

	Scenario							
	Net returns (% change from A)			Total costs (% change from D)				
Year	A	B	C	D	E	F	G	H
2000	69.0	63.4 (−8)	93.2 (+38)	36	36 (0)	35 (−3)	30 (−17)	52 (+53)
2010	78.3	66.6 (−15)	119.8 (+62)	59	59 (0)	55 (−7)	40 (−35)	104 (+113)
2020	80.3	63.0 (−22)	130.6 (+80)	40	72 (+80)	63 (+32)	44 (+6)	155 (+261)
2030	73.2	58.2 (−21)	153.7 (+138)	115	106 (−8)	86 (−27)	56 (−69)	190 (+133)

non-conventional water resources including rainwater harvesting become the main contributors to the water supply. As the unit cost of water from seawater *desalination* decreased from 0.60 to 0.15 \$/m^3 (*scenarios* D–G), the water allocation scheme shifts towards its earlier and greater use, compared to conventional water sources. When the *touristic* demand increases (*scenarios* D and H), the earlier expansion of conventional and non-conventional water resources is required. Note that in this study the analysis was based on a wet season equivalent and in practice the effect of the dry-season on water availability and allocation should be considered.

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Notes

1. The Awali river project proposes the treatment and transfer to Beirut of 520,000 m3/day in two phases: Phase I (260,000 m^3/day) and Phase II (520,000 m^3/day) (ACE, 2000; Montgomery Watson, 1998; 2001; GIBB-KA-KCIC, 1997).
2. Currently, there is only one pre-treatment facility in operation South of Beirut with several other major projects in progress (CDR, 2001). It is anticipated that 80 percent of the water consumed, being domestic, industrial, or touristic, reaches the sewer system (ACE, 2000). Of these, 80 percent can be recycled, which amounts to 64 percent of water consumed (Al-Lababidi, 1999).
3. Although Lebanon has no desalination plants at the time being, this option may be needed to satisfy future water demand if judged economically and environmentally feasible, particularly for the GBA. The main obstacle to desalination remains its relative high cost which is expected to be offset by innovative technology (El-Fadel, 2002; ESCWA, 1999b).
4. Average precipitation in the GBA ranges between 700 and 1,100 mm per year depending on the location. This range lies above the minimum average precipitation of 600 mm/year for the

feasibility of installing rainwater harvesting systems (TWDB, 1997). With 900 mm/year taken as an average over the 253 km^2 of the GBA, the total rainfall is estimated at 228 MCM/year. Assuming that this rainfall occurs in 90 days of the 6 months wet period, this amounts to 2.5 MCM/day. Averaged over the six months of the wet season, this amount becomes 1.25 MCM/day. Assuming that built areas cover 30 percent of the GBAs area, a roof systems efficiency factor of 80 percent, and an evaporation rate of 20 percent, the total amount of rainfall that can be captured through roof systems is estimated at 242,880 m^3/day. As for hill lakes, the GBA is characterized by a high demographic expansion accompanied with high population density. Therefore, unless hill lakes are located outside the GBA, this option is not applicable.

5. For each source of supply, i, the sum of water allocated for each sector, j, should not exceed the water available from this source. The fact that a water supply source has a maximum capacity imposes a sealing on this source. Lowering maximum capacities may play a major role in the sensitivity analysis if the decision maker wants to force a shift from a certain water allocation management alternative to another. Minimum capacities for all sources were set to zero to give the model the freedom of selection.
6. For each sector j, the sum of water supplied from all the sources, i, should be greater or equal to the demand in this sector.
7. The optimum water resources allocation plan can be constrained by decision makers through policy implementation depending on specific economic, social, and environmental objectives. Examples of policy constraints would be the implementation of a certain tariffication scheme, the exclusion of a source as a potential water supply for a certain sector, such as reclaimed wastewater for domestic use, to account for public acceptability, and the reservation of groundwater resources as an emergency supply source to avoid resources depletion and its effects.

References

Associated Consulting Engineers (ACE), 2000, ‘Study and Design for Greater Beirut Water Supply and Wastewater Development. Phase I: Feasibility Study and Preliminary Design’, *Final Report*, Volume I, Council for Development and Reconstruction, Beirut, Lebanon (November).

Al Hajjar, Z., 2001, ‘The Reality of Water in Lebanon’, *Proceedings of the third Hariri Foundation Alumni Association conference in Beirut: Water in Lebanon and the Middle East*, 18 April, Beirut (in Arabic).

Al Hajjar, Z., 1997, ‘Organization of the Water Authorities in Lebanon’, *Report for the Government of Lebanon*, Ministry of Water Resources and Electricity (in Arabic).

Al-Lababidi, A. M., 1999, ‘Environmental Standards Related to Projects of Wastewater Collection, Treatment, Disposal, and/or Reuse’, *Proceedings of Expert Group Meeting on Harmonization of Environmental Standards in the ESCWA Member States*, 28 September–1 April, Beirut (E/ESCWA/ENR/1999/WG.2/5).

Asano, T., 1998, *Wastewater Reclamation and Reuse*, Water Quality Management Library, Volume 10, Technomic Publishing Co. Inc., Lancaster, Basel.

Awaida, K., 2000, Qasmieh Ras El Ain Irrigation Scheme: IRMP, Irrigation Rehabilitation and Modernization Project Works, Project Ending, Litani River Authority, Lebanon.

Council for Development and Reconstruction (CDR), 2001, Wastewater: Achievements to Date, Report, March 2001; available from http://www.cdr.gov.lb/cdr/2001/english/Ewaste.htm; Internet accessed 4 June 2002.

Chaabouni, A., 2001, Interview by author, Ain El Delbeh Water Authority, Lebanon.

Dinar, A., Rosegrant, M. W., Meinzen-Dick, 1997, Water Allocation Mechanisms, Principles and Examples, World Bank, Working Paper (June); available from http://econ.worldbank.org/docs/598.pdf; Internet accessed 16 March 2002.

El-Fadel, M., Maroun, R., Semerjian, L., and Harajli, H., 2003, 'A health-based socio-economic assessment of drinking water quality', *Environ. Manage. Health* **14**(3), 353–368.

El-Fadel, M., Zeinati, M. and Jamali, D., 2002, 'Water resources management in Lebanon: Institutional capacity and policy options', *Water Policy* **3**(5), 425–448.

Economic and Social Commission for Western Asia (ESCWA), 1999, 'Updating the Assessment of Water Resources in the ESCWA Member States', *Proceedings of Expert Group Meeting on Updating the Assessment of Water Resources in the ESCWA Member States*, 20–23 April 1999, Beirut (E/ESCWA/ENR/1999/WG.1/7).

Ghannam, J., Ayoub, G., and Acra, A., 1998, 'A profile of the submarine springs in Lebanon as a potential water resource', *Water Int.* **23**(3), 278–286.

GIBB-KA-KCIC Joint Venture, 1997, Awali Conveyor Project for Beirut Water Supply: Financial and Cost Analysis Study, Second and Third Year Components of the NERP in the Water and Wastewater Sectors in Greater Beirut, Project No. 1020, Contract No. 6183, Council for Development and Reconstruction and the Ministry of Hydraulic and Electric Resources (January).

Montgomery Watson, 2001, 'Awali Beirut water conveyor project: Potential demand for potable water in Greater Beirut' (April).

Montgomery Watson in association with Engico, 1998, European Capital, Hannah & Mould. Awali-Beirut Water Conveyor Project (on BOT basis), Phase I Interim, EA Report, Project no. 1026, Contract no. 6682, Council for Development and Reconstruction (April).

Nimeh, M., 2001, Interview by author, American University of Beirut, Lebanon.

Texas Water Development Board (TWDB), 1997, 'Texas Guide to Rainwater Harvesting', In Cooperation with Center for Maximum Potential Building Systems, Second edition, Austin, Texas; available from http://www.twdb.state. tx.us/publications/reports/RainHarv.pdf; Internet accessed 30 April 2002.

United Nations Environmental Program (UNEP), 1997, Sourcebook of Alternative Technologies for Freshwater Augmentation in Latin America and the Caribbean, Unit of Sustainable Development and Environment General Secretariat, Organization of American States, International Environmental Technology Center, Washington, DC; available from http://www.Oas.org/used/publications/unit/oea59e/begin.htm#Contents; Internet accessed 25 April 2002.

Verheem, R. A. A. and Tonk, J. A. M. N., 2000, Strategic Environmental Assessment: One Concept, Multiple Forms, *Impact Assess. Project Appraisal, IAIA*, **18**(3), 177–182.

World Bank (WB), 2001, Middle East and North Africa, Water pricing and sanitation, Water Pricing in the Municipal Sector; available from http://wbln0018.worldbank.org/mna/mena.nsf/All/3A6237E81F44D9F0852569490070AF6B?OpenDocument; Internet accessed 20 April 2002.

Yamout, G. M., 2002, 'An Optimization Model for Water Supply Multi-Sectoral Allocation in the Greater Beirut Area', *M.S. Thesis*, Faculty of Engineering and Architecture, American University of Beirut, Beirut, Lebanon.