

Integrated Optimization of a Dual Quality Water and Wastewater System

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Abstract: When addressing urban water problems, it is no longer adequate to consider issues of water supply, demand, disposal, and reuse independently. Innovative water management strategies and opportunities for water reuse can only be properly evaluated in the context of their interactions with the broader water system. An integrated linear deterministic optimization model is applied to Beirut, Lebanon, to determine the minimum cost configuration of future water supply, wastewater disposal, and reuse options for a semiarid coastal city. Previous urban water system optimization models considered only a single quality of potable water and were thus unable to demonstrate the cost-effectiveness of reclaimed water among all viable options for water supply. Two innovations of our work include incorporation of the entire anthropogenic water cycle including interconnections between supply, demand, disposal, and reuse and modeling of the suitability of nonpotable and potable qualities of water for each demand sector. The optimization model yields surprising insights. For example, after full use of inexpensive conventional sources, nonpotable direct reuse appears to be Beirut's most cost-effective option for supply of its urban nonpotable and irrigation demands. Our work highlights the importance of modeling the utility of multiple qualities of water in modern water supply planning.

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Introduction

The majority of the world's population is clustered in urban areas along the coast or inland water systems. By 2010 more than 50% of the world's population is expected to live in urban areas (Mas-soud et al. 2004). The water managers of urban areas worldwide will face stiff challenges as they seek reliable sources of fresh water for their burgeoning populations. Because of the possibilities for economies of scale, high value uses of water, and the close proximity of water users and wastewater generators, urban and semiurban areas have great potential to take an integrated approach to water supply and wastewater management. In the framework of integrated water resources management, all sources of water, including reclaimed wastewater, hold potential as supply sources, and the multiple quality needs of users are recognized.

We introduce an optimization model designed to assist in

water supply systems planning in Greater Beirut, Lebanon. Our model formulation is designed specifically to evaluate the cost-effectiveness of wastewater reclamation and urban reuse in addition to other viable alternatives for water supply.

Greater Beirut currently experiences water shortages in the dry season and increases in population, economic development, tourism, and the adverse effects of climate change are anticipated, all of which are likely to further stress the water system. Beirut is actively seeking solutions to its escalating water supply and demand concerns. Among its most promising options are: (1) reduction of distribution system losses; (2) demand management; (3) acquisition of new water sources; and (4) adoption of alternative water supply technologies such as desalination and water reuse (El-Fadel et al. 2001; Ayoub and Chammas 2006). This study addresses only options 3 and 4, considering a planning horizon of the next 25 years.

Literature Review

Numerous previous studies have developed optimization models for complex urban and semiurban water supply systems [see, for example, Delucia and Rogers (1972); Kirshen (1979); Draper et al. (2003)] and wastewater management systems [see, for example, Mandl (1981); Leighton and Shoemaker (1984); Fu et al. (2008)]. Optimization models have also been applied to a number of water and wastewater problems in and around Beirut (Darwish et al. 1999; Al-Weshah 2000; El-Awar et al. 2001; Najm and El-Fadel 2004; Yamout and El-Fadel 2005). While other studies have optimized wastewater reuse for agricultural purposes [see, for example, Afshar and Mariño (1989); Oron (1996); Darwish

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et al. (1999)], those studies did not model the linkages between wastewater treatment and urban water reuse.

In order to evaluate the cost-effectiveness of wastewater reclamation and urban reuse, it is necessary to consider demands for water of different qualities. Our model incorporates the demand for two grades: nonpotable and potable. This is not the first study to incorporate supply of water of various qualities in a water system model [see, for example, Liang and Nnaji (1983); Mehrez et al. (1992); Brimberg et al. (1993); Percia et al. (1997); Campbell et al. (2002); Tu et al. (2005)]. It is, we believe, the first to consider urban demand for nonpotable water.

So far as we are aware, no other study has developed an optimization model of the entire anthropogenic water cycle, including the interconnections among supply, demand, disposal and reuse, and urban demands for water of multiple qualities. Our model, of course, does not optimize every element of the anthropogenic water system. Within the bounds of a coastal city, our model tracks all water withdrawn from natural sources for urban and agricultural uses, including its potential reuses, until it is discharged from the anthropogenic system. The optimization algorithm explores the cost-effectiveness of small-scale on-site water treatment, recycling, and disposal, as well as large-scale centralized supply and disposal. Consequently, both direct and indirect forms of water reclamation and reuse feature prominently in the model, which effectively reshapes the water system allocation and reveals new opportunities for cost reductions.

Previous studies reviewed in this section have used both linear and nonlinear solution techniques. The problem described here has been structured as a linear program because extremely efficient solution methods are available for large linear programming problems such as this one (Revelle et al. 2004; Loucks and Van Beek 2005). A sensitivity analysis suggests that the integrity of the formulation was not significantly diminished by the approximations made in the process of linearization.

The following section describes the structure of the model and its application to Beirut. The model formulation section describes the objective function and constraint equations, which can be found in the appendix. The results of probable scenarios are examined before conclusions are offered summarizing the ramifications of the findings.

Model Description

Fig. 1 presents a generalized schematic of the human portion of the water cycle encompassing all water and wastewater infrastructure associated with a semiarid coastal city. Human water use is typically divided into three sectors: municipal (MU), industrial (I), and agricultural (AG). We further divide the industrial sector into food-related industry (IA) and nonfood-related industry (IB). The municipal and industrial sectors are categorized as urban sectors and assumed to be located exclusively within the city. Municipal water use is composed of residential, commercial, and tourism uses. Agricultural land in the vicinity of the coastal city is assumed to be located on its inland periphery and all rural land is assumed to be mostly agricultural. All agricultural and urban sectors have use for both potable (P) and nonpotable (N) water.

Water flows from sources on the left-hand side of Fig. 1 to demand sectors, then to disposal sites on the right-hand side of Fig. 1. The disposal sites supply water for reuse depending upon the level of treatment. For on-site recycling, water moves from the waste side of a potable use through on-site treatment to the

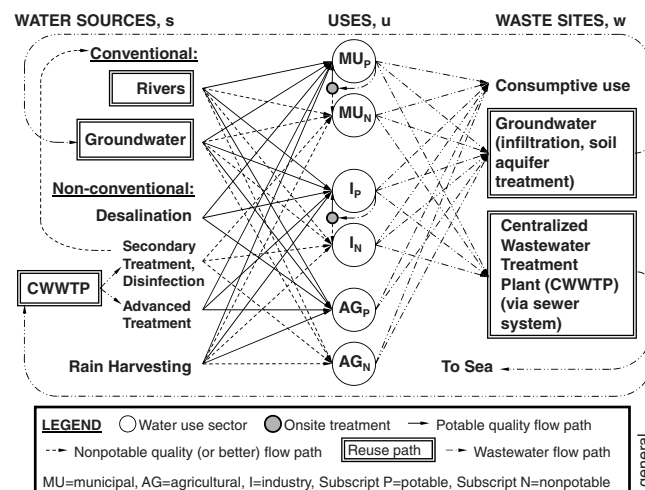


Fig. 1. Generalized flow schematic of the anthropogenic water cycle

supply side of either a potable or nonpotable use, depending upon the level of treatment.

The double-bordered boxes in Fig. 1 represent pathways for reuse, which serve to close the water loop. Wastewater may not be returned to rivers or aquifers without first receiving treatment, either centrally or on site. Wastewater treated on site can infiltrate into groundwater or be reused. Water treated within the centralized wastewater treatment plant (CWWTP) is available for several reuse applications, depending upon the level of treatment.

Raw water from all natural sources is classified as nonpotable, whether drawn from surface water sources, groundwater sources, or rainwater harvesting. It is understood that virtually all surface water sources, and most groundwater sources (especially those in urban environments), require filtration and disinfection before they qualify for consumption.

During *reclamation and reuse*, wastewater is collected, treated to a level of purity appropriate for the intended reuse, and returned to water users. Water *recycling* is on-site water reclamation and reuse. During *indirect reuse*, partially treated wastewater is further treated after discharge by physical and biochemical processes in the receiving water. Water *reused directly*, without first being returned to the natural system, requires more extensive treatment as a substitute for that normally provided by nature. *Consumed* water is permanently removed from the system by its use, is not added to the wastewater collection system, and is therefore unavailable for reuse (Crook 1998).

Greater Beirut Water Resources and Infrastructure

Fig. 2 locates the semiarid coastal city under consideration, Greater Beirut, and identifies its principal water treatment plants and wastewater treatment plant (WWTP). The 253 km² geographical extent of Greater Beirut includes Beirut City and parts of the administrative regions of Baabda, Metn, Aley, and Chouf. Lebanon has been called "the Switzerland of the Middle East," in part because the diminutive country of approximately 10,400 km² ascends rapidly from sea level to over 3,000 m within a horizontal distance of less than 30 km. The average annual temperature in Beirut is 20°C, with an average annual precipitation of 825 mm. Almost all of Lebanon's annual precipitation occurs in the form of heavy rains during 80–90 days of the winter season. Fig. 1 presents the water supply, wastewater disposal, and reuse options potentially available to Greater Beirut

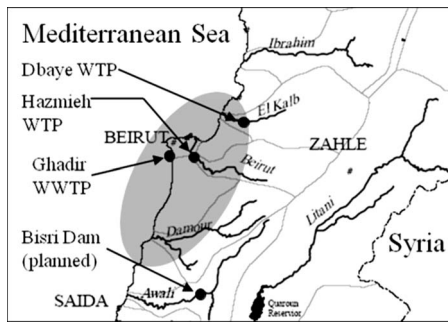


Fig. 2. Study area [adapted from Lebanon Ministry of Environment and Lebanon Environment & Development Observatory (LEDO) (2001)]

and Table 1 summarizes the water requirements and maximum water availability projected to 2030. Much of the data used here were derived from El-Fadel et al. (2000) and Yamout and El-Fadel (2005) and have been presented in greater detail in Ray (2006).

Lebanon does not have well-established national standards for the use of reclaimed wastewater. Instead, it refers to guidelines adopted by the United States Environmental Protection Agency (Angelakis et al. 1999; Ayoub and Chammas 2006). United States Environmental Protection Agency (USEPA) (2004) differentiates between activities requiring potable water (such as drinking or food preparation) and activities (such as toilet flushing) for which nonpotable water is sufficient. Within those categories, approximately 83% of the agricultural demand within Greater Beirut can be met by nonpotable water (Crook 1998; LEDO 2001; Ray 2006). The municipal sector requires that 70% of its total demand be met by potable water and the food-related industrial sector (Industry Type A) requires 95% potable water (Metcalf and Eddy 2003; Ray 2006). Nonfood-related industry (Type B), with a heavy emphasis on cooling and cleaning, is assumed to use equal

Table 1. Projected Year 2030 Water Supply and Demand within Greater Beirut

	Wet season (m ³ /day)	Dry season (m ³ /day)
Water demand sector		
Municipal	808,000	824,000
Industrial Type A	170,000	170,000
Industrial Type B	307,000	307,000
Agricultural	0	30,000
Total	1,285,000	1,331,000
Water supply source		
El-Kalb River (ER)	500,000	104,000
Beirut River (BR)	73,000	29,000
GA	13,200	22,800
GB	96,800	167,200
Total	683,000	323,000
<i>Awali River, Phase I (A1)</i>	<i>260,000</i>	<i>260,000</i>
<i>Awali River, Phase II, Bisri Dam (A2)</i>	<i>260,000</i>	<i>260,000</i>
<i>Rainwater</i>	<i>238,900</i>	<i>0</i>
<i>Harvesting (RH)</i>		
<i>Desalination (DS)</i>	<i>Unbounded</i>	<i>Unbounded</i>
<i>Water reuse (WW)</i>	<i>Variable</i>	<i>Variable</i>

Note: Proposed but currently nonexistent infrastructure in italics.

quantities of nonpotable and potable waters. The fraction of total water demand in each urban sector that must be met by potable water is assumed to be constant throughout the year.

Facilities related to the acquisition and treatment of water from the El-Kalb River, Beirut River, inland aquifer (GA), coastal aquifer (GB), and the associated distribution system are already in place. Table 1 summarizes the maximum daily withdrawals from each source. Since the yield of the aquifers beneath Greater Beirut is unknown, Table 1 assumes the continuation of historical withdrawal practices, which may or may not be sustainable. Desalination plants, water reclamation and reuse facilities, rainwater harvesting infrastructure, and facilities for the supply of water to Greater Beirut from the Awali River have been proposed but are not yet in place.

The CWWTP and collection system are already in place. As of 2005, the CWWTP was equipped for only preliminary treatment and processed less than 15% of the wastewater generated in Greater Beirut. We assume that the treatment plant will be upgraded for secondary treatment of nearly 100% of the wastewater generated in Greater Beirut by the year 2030 [Council for Development and Reconstruction, Lebanon (CDR) 2004]. The wastewater from the urban sectors (municipal and industrial) may be treated and discharged to groundwater on site or piped to a CWWTP for bulk treatment and discharge to the sea. However, since the karst aquifers beneath Greater Beirut cannot be relied upon for soil aquifer treatment [United States Environmental Protection Agency (USEPA) 2002], treatment to potable quality is required as a prerequisite to aquifer augmentation. Water not consumed by the agricultural sector returns by gravity infiltration to the underlying aquifer from which it may be later withdrawn.

Once fully equipped for secondary treatment, the CWWTP could be upgraded for nonpotable reuse or further upgraded for potable reuse. The potable reuse facility would be an extension of the nonpotable reuse facility and all costs of treatment to potable quality would be incrementally more than the costs of treatment to nonpotable quality. Direct potable reuse would require that the CWWTP be equipped for tertiary treatment including advanced filtration and disinfection. Direct nonpotable reuse would require secondary wastewater treatment plus filtration and disinfection, according to standards defined for urban reuse applications by United States Environmental Protection Agency (USEPA) (2004). Indirect nonpotable reuse would require that the CWWTP be equipped only for secondary treatment and disinfection and would rely upon a river or aquifer for further treatment [Crook 1998; Richard 1998; United States Environmental Protection Agency (USEPA) 2004].

It is assumed that Greater Beirut will reduce its distribution losses from nearly 50 to 20% by 2030 (Yamout and El-Fadel 2005). As suggested by Metcalf and Eddy (2003), losses of 12 and 5% are assumed for the yet uninstalled nonpotable water distribution system and on-site recycle/disposal systems, respectively. Losses of 20% are assumed for the municipal sewage collection system. Infiltration is not expected to contribute to wastewater flows because sewer pipes are mostly positioned above the water table.

Greater Beirut does not have nonpotable water distribution system infrastructure. Delivery of nonpotable water to an urban sector (municipal or industrial) from any source not located at the site of use would require the construction of a nonpotable water distribution system in parallel with the existing potable water distribution system. Indirect reuse would involve transporting reclaimed water from the CWWTP to the point of insertion into the river or aquifer via single large pipelines.

Table 2. Total Unit Costs to Supply, Reuse, and Dispose of Water in Greater Beirut, Year 2000 (\$/m³)

Source	Use site and type				Waste sink			
	Urban _P	Urban _N	AG _P	AG _N	GA	GB ^d	WW ^{c,d}	Losses
El-Kalb River (ER) _P ^a	0.13	0.13	0.13	0.13	—	—	—	0.13
El-Kalb River (ER) _N ^a	—	0.07	0.07	0.07	—	—	—	0.07
Beirut River (BR) _P ^a	0.11	0.11	0.11	0.11	—	—	—	0.11
Beirut River (BR) _N ^a	—	0.07	0.07	0.07	—	—	—	0.07
GA (GA) _P ^{a,d}	—	—	0.14	0.14	—	—	—	0.14
GA (GA) _N ^a	—	—	0.08	0.08	—	—	—	0.08
GB (GB) _P ^{a,d}	0.14	0.14	—	—	—	—	—	0.14
GB (GB) _N ^a	—	0.08	—	—	—	—	—	0.08
<i>Awali R. Phase 1 (A1)_P^a</i>	<i>0.36</i>	<i>0.36</i>	<i>0.36</i>	<i>0.36</i>	—	—	—	<i>0.36</i>
<i>Awali R. Phase 1 (A1)_N^a</i>	—	<i>0.14</i>	<i>0.14</i>	<i>0.14</i>	—	—	—	<i>0.14</i>
<i>Awali R. Phase 2 (A2)_P^a</i>	<i>0.46</i>	<i>0.46</i>	<i>0.46</i>	<i>0.46</i>	—	—	—	<i>0.46</i>
<i>Awali R. Phase 2 (A2)_N^a</i>	—	<i>0.31</i>	<i>0.31</i>	<i>0.31</i>	—	—	—	<i>0.31</i>
<i>Rainwater Harvest (RH)_P^a</i>	<i>3.34</i>	<i>3.34</i>	—	—	—	—	—	<i>3.34</i>
<i>Rainwater Harvest (RH)_N^e</i>	—	<i>3.14</i>	<i>0.66</i>	<i>0.66</i>	—	—	—	<i>0.66</i>
<i>Desalination (DS)_P^b</i>	<i>0.53</i>	<i>0.53</i>	<i>0.53</i>	<i>0.53</i>	—	—	—	<i>0.53</i>
<i>Desalination (DS)_N</i>	—	—	—	—	—	—	—	—
<i>Central WWTP (WW)_P^d</i>	<i>0.93</i>	<i>0.93</i>	<i>0.93</i>	<i>0.93</i>	—	—	—	<i>0.93</i>
<i>Central WWTP (WW)_N^d</i>	—	<i>0.13</i>	—	<i>0.13</i>	—	—	—	<i>0.13</i>
Bottled Water (BW) _P	200.00	200.00	200.00	200.00	—	—	—	—
Bottled Water (BW) _N	—	—	—	—	—	—	—	—
Urban (MU,IA,IB) _P ^d	2.30	1.23	—	—	—	2.30	0.18	—
Urban (MU,IA,IB) _N	—	—	—	—	—	2.30	0.18	—
Agricultural (AG) _P	—	—	—	—	0.00	—	—	—
Agricultural (AG) _N	—	—	—	—	0.00	—	—	—

Note: Proposed but currently nonexistent infrastructure in italics.

^aFrom Yamout and El-Fadel (2005).

^bFrom *Water-technology.net* (2005).

^cFrom Lebanon Ministry of Environment and Lebanon Environment & Development Observatory (LEDO 2001), anaerobic treatment only or activated sludge with anaerobic pretreatment, serving 1.8 M people equivalents.

^dFrom Richard (1998), including economies of scale.

^eFrom Texas Water Development Board (TWDB 1997).

Each on-site treatment facility within the model has a capacity of 3,800 m³/day (~1 MGD), the smallest capacity typically considered economically feasible (Richard 1998). Such a treatment facility would be appropriate for a small neighborhood community or industrial complex.

The quantity of water that can be desalinated is theoretically infinite, assuming that the sea can absorb the concentrated brines produced by the process. The details of brine and sludge disposal are outside of the scope of this model, though the costs associated with each were included in the total cost of treatment.

Greater Beirut Water Costs

Table 2 presents specific features of Greater Beirut's available water and wastewater infrastructure and the associated amortized unit costs of each flow path. Explanations of the nomenclature used in Table 2 are provided in Table 3. Table 2 is divided into four quadrants. The upper-left quadrant summarizes permissible flow paths for water supply from sources to uses. Recall that the urban sector includes municipal and industrial uses. Unit costs of water from potable sources (subscript P) include the costs of treatment. The lower-left quadrant summarizes permissible flow paths for on-site recycling and their associated unit costs, including treatment to the appropriate level of water quality. The lower-right quadrant presents unit costs and permissible flow paths for

wastewater, which may be discharged either locally to groundwater or centrally to the sea. The upper-right quadrant presents the costs of water consumed or lost in the distribution or collection system, which carries the same cost as water arriving at a site of use. Water lost in the recycle system or collection system carries no cost as it does not receive treatment.

The average life of water and wastewater treatment facilities is assumed to be 20 years and the interest rate used is 10%. It is assumed that the ratio of operation and maintenance (O&M) costs to capital costs for smaller treatment facilities (less than 10 MGD) is similar to the ratio of O&M to capital costs for larger treatment facilities (greater than 100 MGD) and that the relative costs of the treatment technologies considered will be the same in the year 2030 as they are now (Richard 1998).

Facilities demonstrating significant economies of scale require adjustment of their unit cost values depending upon their size. Based upon cost values reported for recently constructed desalination facilities in Tampa, Florida and Israel, it is assumed that large desalination facilities between approximately 130,000 and 330,000 m³/day demonstrate no significant economies of scale [Peter Rogers, personal communication, February 27, 2005; Tufts University, Medford, Mass. (2005)].

Water reclamation and reuse plants, however, do seem to demonstrate economies of scale (see Ray 2006). The cost values pre-

Table 3. Model Nomenclature

Symbol	Description
Sources of water (capital letters)	
ER_P	Potable water from the El-Kalb River
ER_N	Nonpotable water from the El-Kalb River
BR_P	Potable water from the Beirut River
BR_N	Nonpotable water from the Beirut River
$A1_P$	Potable water from the Awali River, Phase I
$A1_N$	Nonpotable water from the Awali River, Phase I
$A2_P$	Potable water from the Awali River, Phase II (Bisri Dam)
$A2_N$	Nonpotable water from the Awali River, Phase II (Bisri Dam)
RH_P	Potable water from rainwater harvesting
RH_N	Nonpotable water from rainwater harvesting
DS_P	Potable water from desalination
DS_N	Nonpotable water from desalination
GA_P	Potable water from Groundwater Aquifer A—GA
GA_N	Nonpotable water from Groundwater Aquifer A—GA
GB_P	Potable water from Groundwater Aquifer B—GB
GB_N	Nonpotable water from Groundwater Aquifer B—GB
WW_P	Potable water from CWWTP
WW_N	Nonpotable water from CWWTP
BW_P	Potable bottled water
BW_N	Nonpotable bottled water
Uses for water (capital letters)	
MU_P	Municipal potable water use
MU_N	Municipal nonpotable water use
IA_P	Food-related industrial potable water use
IA_N	Food-related industrial nonpotable water use
IB_P	Nonfood-related industrial potable water use
IB_N	Nonfood-related industrial nonpotable water use
AG_P	Agricultural potable water use
AG_N	Agricultural nonpotable water use
Waste sites (capital letters)	
GA	Groundwater Aquifer A—GA
GB	Groundwater Aquifer B—GB
WW	CWWTP
CL	Consumptive loss
Sets (lowercase letters)	
s	Sources of water
gs	Grade of source water, either potable or nonpotable
u	Uses of water
	Grade requirement for given use, potable or nonpotable
gu	
r	Sources and uses for recycled water, alias for u
gr	Grade of recycled water, either potable or nonpotable
w	Waste sites
ts	Time, season, either wet or dry
Coefficients (lowercase letters)	
fc_{2005}	Fraction of water users connected to sewer system in 2005
cn_{pds}	Total annualized unit cost of nonpotable distribution system (\$/m ³)
fn_{pdsom}	Fraction of total annualized unit cost of npds incurred as O&M
$days_{ts}$	Number of days in each season (days)
$f_{dsl_{s,gs}}$	Fraction of water from each grade, gs , of each source, s , lost in distribution system

Table 3. (Continued.)

Symbol	Description
f_{csl_s}	Fraction of water intended for reuse sites, s , that is lost in the collection system
f_{wsl_w}	Fraction of water intended for waste sites, w , that is lost in the collection system
f_{rsl_u}	Fraction of water from each use, u , lost in the recycle system
f_{xsl_s}	Fraction of water intended for each source, s , lost in indirect reuse lines
f_{reuse_s}	Fraction of reclaimed wastewater eligible for indirect reuse at each source site, s
b_{aug_s}	Binary coefficient indicating fitness for augmentation with reclaimed wastewater (1=augmentable, 0=nonaugmentable) of each source, s
n_{ts}	Number of seasons, ts , injected wastewater must remain in ground before being withdrawn and reused
$f_{som_{s,gs}}$	Fraction of total annualized unit cost of new supply facilities, s , of each grade, gs , incurred as O&M
f_{wom_w}	Fraction of total annualized unit cost of new wastewater treatment facilities, w , incurred as O&M
$f_{rom_{r,gr}}$	Fraction of total annualized unit cost of new on-site treatment facilities, r , of each grade, gr , incurred as O&M
f_{xom_s}	Fraction of total annualized unit cost of indirect reuse facilities, s , incurred as O&M
$q \max_{s,ts}$	Maximum flow from each source, s , in each season, ts (m ³ /day)
$q \min_{u,ts}$	Minimum flow to each use, u , in each season, ts (m ³ /day)
$f_{g_{u,gu,ts}}$	Fraction of water use, u , to be met by each grade, gu , of water in each season, ts
$f_{recyc_{u,gu,ts}}$	Fraction of water from each sector, u , of each grade, gu , that can be recycled in each season, ts
$f_{cl_{u,gu,ts}}$	Fraction of each grade, gu , of water consumed at each use sector, u , in each season, ts
$cs_{s,gs,u,gu}$	Cost to supply water from each grade, gs , of each source, s , to each grade, gu , of each use sector, u (\$/m ³)
$cw_{u,gu,w}$	Cost to dispose of wastewater from each grade, gu , of each use, u , at each waste site, w (\$/m ³)
$cr_{u,gu,u,gu}$	Cost to recycle water of each grade, gu , from each sector, u , to each grade, gu , of itself, u (\$/m ³)
cx_s	Cost to augment conventional water sources, s , with water from CWWTP (\$/m ³)
Variables (capital letters)	
$Q_{s,gs,u,gu,ts}$	Flow from each grade, gs , of each source, s , to each grade, gu , of each use sector, u , in each season, ts (m ³ /day)
$Q_{w_{u,gu,w,ts}}$	Wastewater flow from each grade, gu , of each use sector, u , to each waste site, w , in each season, ts (m ³ /day)
$Q_{r_{u,gu,u,gu,ts}}$	Recycle flow from each grade, gu , of each use sector, u , to each grade, gu , of itself, u , in each season, ts (m ³ /day)
$Q_{x_{s,ts}}$	Water treated by WWTP to augment conventional water sources, s , in each season, ts (m ³ /day)
$Q_s \max_{s,gs}$	Maximum capacity of each grade, gs , of each proposed supply source, s (m ³ /day)
$Q_w \max_w$	Maximum capacity of proposed new secondary wastewater treatment facility, w (m ³ /day)
$Q_r \max_{u,gu}$	Maximum capacity of each grade, gu , of all on-site treatment facilities in each use sector, u (m ³ /day)

Table 3. (Continued.)

Symbol	Description
$Q_{\max npds}$	Maximum capacity of nonpotable water distribution system (m^3/day)
Objective: minimize total cost	
Z	Total cost to supply, reuse and recycle water, and dispose of wastewater for the year (\$/year)

sented in Table 2 assume water reuse treatment plants on the order of 400,000 m^3/day for both potable and nonpotable reuse plants. See the discussion of Scenario 4 for an explanation of the adoption of water reuse plants significantly deviating from the assumed size.

Richard (1998) estimated life-cycle costs for retrofitted reclaimed water distribution systems to be \$0.28/ m^3 in year 1996 dollars (\$0.32/ m^3 in year 2000 dollars). Crook (personal communication, 2005) reasoned that treatment costs might be only one-third of total reclaimed water delivery costs, which would suggest distribution system costs near \$0.26/ m^3 , based upon nonpotable system treatment costs of \$0.13/ m^3 . In keeping with the reasoning of each, a value of \$0.30/ m^3 was selected for construction, operation, and maintenance of nonpotable water distribution lines. When nonpotable water is supplied to the urban sector, the model adds the amortized unit cost of the nonpotable water distribution system to the amortized unit cost of nonpotable water from the source.

Model Formulation

The linear programming model is static and deterministic with a planning horizon of one year, which is divided into a wet season and dry season. Our objective is to minimize the total cost of providing water of appropriate quality to all endogenous anthropogenic water users and disposing of the wastewater generated.

Objective Function

In the interest of brevity, objective function and constraint equations are included in the Appendix. This and the following section call attention to those particular constraints requiring explanation. Ray (2006) provided comprehensive descriptions of the other constraints.

Our objective is to minimize the sum of all water supply, wastewater disposal, and water reuse costs, including O&M costs and capital costs, of all alternatives. When the source, waste sites, or infrastructure are already in place, the objective function only includes O&M costs. When new facilities are considered, the objective function includes both capital and O&M costs. O&M costs are charged per unit of water supplied or wastewater discharged

or reused. Amortized capital costs for the full capacity of newly constructed facilities are charged each season regardless of the degree to which the facilities are utilized.

Costs are incurred at each source of supply and each site of disposal. Water lost in the recycle system, $frsl_w$, and collection system, fcs_l_w , carries no cost as it does not receive any treatment. Consumption is modeled as a waste flow and, therefore, incurs no charges. Nonpotable distribution system costs apply only to urban nonpotable demands supplied by sources not on site.

Constraints

Eqs. (2)–(4) conserve volume, determine the volume consumed in each sector in each season, and apply technological limitations to recyclable fractions. Eq. (5) enforces the supply limits at each source in each season. The CWWTP and each groundwater aquifer are unique as potential sources of reclaimed water and equations limiting their production of water require special cases of (5). Constraints (6) and (7) limit flow from the inland (GA) and coastal (GB) aquifers, respectively. In addition to the natural sustainable yield, $q_{\max,ts}$, and any source augmentation with reclaimed water from the CWWTP, the maximum flow from aquifers GA and GB can be increased by the reusable fraction, $freuse_s$, of the quantity of wastewater treated and discharged on site, $Q_{w_{u,gu,w,ts}}$, after collection system losses, fcs_l_w . GA receives water infiltrated from the agricultural sector and GB receives water infiltrated from the urban sectors. Finally, water is available for withdrawal from each aquifer a number of seasons, n_{ts} , after it was discharged to the aquifer, as dictated by the aquifer gradient and geology.

We place an upper bound on aquifer recharge so that the algorithm does not find it cost-effective to inject an unreasonably large flow of reclaimed wastewater into the aquifer beneath the city. Constraints (8) and (9) limit the total amount of indirect reuse that each aquifer can receive to twice its natural safe yield.

In keeping with the United States Environmental Protection Agency (USEPA) (2004) suggested guidelines for reuse, agricultural water demand is handled separately from municipal and industrial water demands. Untreated water from all conventional sources is acceptable for all kinds of irrigation. However, reclaimed water used for irrigation of foods to be eaten raw must meet potable water standards. In the event that agricultural potable demand is to be met by reclaimed water, the cost structure within the algorithm (see Table 2) requires that the reclaimed wastewater be treated to potable standards.

As enforced by Constraint (13), desalination capacity must be established within the model (and capital costs registered) before desalinated water can be supplied to demands. Other constraints on the use of proposed facilities, similar in structure to Constraint (13), can be found in Ray (2006).

Table 4. Summary of Results

Scenario	Total water supplied ($Mm^3/year$)	Total cost (supply, reuse, disposal) (\$M/year)
Conventional sources only	Infeasible	Infeasible
Potable supply only (no nonpotable supply)	478	297
Base	478	272
Climate change+triple tourists+allow aquifer recharge with nonpotable water+desal at \$0.35/ m^3	490	237

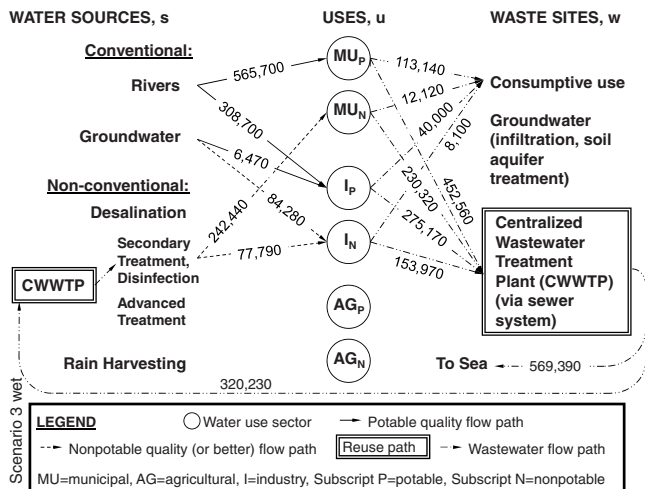


Fig. 3. Scenario 3 wet season schematic results (m³/day)

Results and Discussions

Table 4 summarizes the results of the scenarios considered. Scenario 1, the use of conventional sources only, is infeasible, as confirmed by Beirut's current periodic water shortages in the dry season. Scenario 2 models the prevailing approach to water supply, in which all water supplied for all uses is of potable quality. The base scenario, Scenario 3, is discussed in depth below. In contrast to the base scenario, Scenario 4 considers the cumulative effects on Greater Beirut of climate change, a three-fold increase in tourism, a relaxation of nonpotable water discharge standards, and a decrease in the cost of desalination.

Scenario 3: Base Case

The model formulation for the base scenario, developed using demand and supply values projected to the year 2030, was described in the Model Formulation section. Figs. 3 and 4 present wet- and dry-season results, respectively, for the base scenario. Distribution system losses have been removed from the use sector influent but collection system losses have not been removed from

the use sector effluent. Collection system losses have been removed from waste flows from waste sites to sites of disposal or reuse.

The model was solved using the simplex algorithm in GAMS (Brooke et al. 1992). The code written for the base scenario includes 124 equations, 540 variables, and 2,802 nonzero elements. The only nonbinding sets of constraints are Eqs. (4), (8)–(10), and (6) (wet season), meaning that, in this scenario, there is a capacity for further utilization of all types of water reuse (on-site recycling and centralized direct and indirect reuses).

As expected, the optimization algorithm generally allocated water in the order of increasing cost, as summarized in Table 2. In the wet season, treated water from rivers was the primary supply source for urban potable uses. Untreated groundwater, withdrawn on site, was applied to industrial nonpotable demands. A small amount of groundwater was withdrawn and treated centrally, added to the distribution system, and applied to industrial potable uses. Because conventional sources were insufficient to supply all of the demand, the optimization algorithm recommended that nonpotable reuse of water reclaimed from the CWWTP, including the installation of a nonpotable water distribution system, be instituted to satisfy much of the nonpotable water demand. The model did not recommend on-site treatment and disposal or recycling.

In the dry season, as in the wet season, the algorithm allocated rivers for potable uses and aquifers principally for nonpotable uses. The same quantity of water was reused in both seasons. However, due to increased dry-season demands and decreased dry-season river flows, the model also recommended desalination of Mediterranean Sea water in order to satisfy urban demand for potable water. Agricultural water demand was met by both groundwater and water reclaimed from the CWWTP. The algorithm again recommended that all urban wastewater be treated at the CWWTP.

In each season the algorithm recommended that nonpotable urban demands be met exclusively by nonpotable sources. Nonpotable reclaimed water, treated at the CWWTP, is a cost-effective option for supply of urban nonpotable demands even when the cost of nonpotable water pipelines is included. The total annual cost of allocating 478 Mm³ per year to Beirut within the base scenario was approximately \$272M. Alternative optima exist, as a number of sources can interchangeably supply water to either the municipal or industrial sectors for the same cost.

If desalinated water were used instead of reclaimed water to supply urban nonpotable demands, the additional cost would be approximately \$18.1M (7%) per year. If nonpotable water were disqualified entirely as a water supply option, for both urban and rural applications (Scenario 2) then the increased reliance on desalination would increase the annual expenditures for water supply by \$25M (9%) relative to the base scenario.

Scenario 4

Though many scenarios were explored [see Ray (2006)], we summarize only Scenario 4 here because it combines elements of the most compelling scenarios and presents their cumulative effects. Mutasem El-Fadel (personal communication, July 2005) anticipated that over the next 25 years Beirut will see a sharp increase in tourism and summertime water-intensive recreation activities involving water parks, playing fields requiring irrigation, and swimming pools. Additionally, Bou-zeid and El-Fadel (2002) suggested that climate change and desertification in Lebanon might increase the agricultural demand for water by as much as 6%

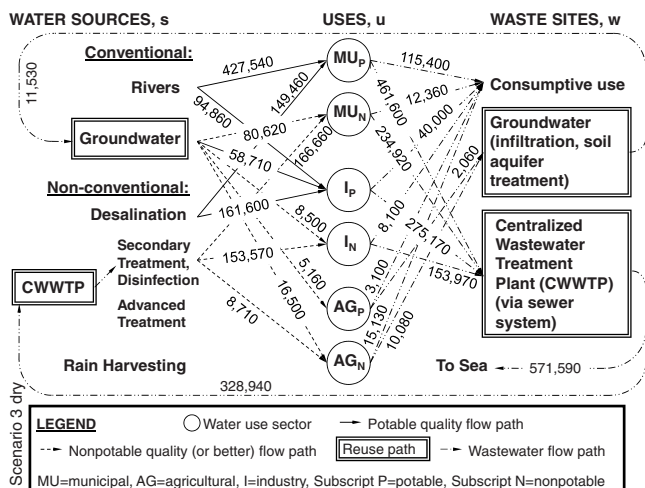


Fig. 4. Scenario 3 dry-season schematic results (m³/day)

while decreasing the amount of water available from conventional sources by as much as 15% by the year 2020. This scenario therefore increased agricultural demand by 6% and decreased by 15% the water available from rivers and aquifers.

It is possible that Greater Beirut will adopt less stringent reuse guidelines than those put forth by the United States Environmental Protection Agency (USEPA) (2004) in order to allow aquifer recharge using nonpotable water reclaimed from the CWWTP or from smaller on-site treatment facilities. It was assumed that under the stress of climate change and increasing tourism, the Beirut Water Authority would consider nonpotable aquifer recharge.

Finally, the cost of seawater desalination has fallen by almost 50% in the last 15 years and is likely to continue to drop in the next 25 years, possibly reaching values as low as \$0.35/m³ by 2030 (Mutaseem El-Fadel, personal communication, July 2005).

The most interesting differences between this scenario and the base scenario are found in the model's use of desalination and nonpotable indirect reuse. The GB was fully augmented with nonpotable water reclaimed from the CWWTP in both the wet and dry seasons. The additional groundwater was applied to nonpotable urban uses in both seasons and to irrigation in the dry season. Desalinated water was used mostly for potable purposes. Approximately 25% of the nonpotable demand in the wet season and 26% of dry-season nonpotable demand was met by potable desalinated water.

In Scenario 4 the model recommended almost 1.2 Mm³/day of desalination in the dry season. A desalination plant capable of that load does not exist yet but may become attractive under the cost conditions upon which this scenario is based. It was assumed that three separate 400,000 m³/day desalination plants would be required.

The cost of reclaimed water from the CWWTP was adjusted to account for the small size of the tertiary treatment facilities in this scenario. The increase did not significantly alter the resulting water allocation but did increase the total cost of the allocation by approximately \$1M per year. The total annual cost of allocating 490 Mm³ to Greater Beirut within this scenario was approximately \$237M. In this case, the elevated demand was offset by the radically reduced cost of desalination.

The results of this scenario are sensitive to the coefficient assigned to the maximum allowable augmentation of each aquifer in constraints (8) and (9). Doubling the coefficient from 2 to 4 reduces the total cost of this scenario by 4.2% (from \$237M to \$227M). Halving the coefficient from 2 to 1 increases the total cost of this scenario by 2.1% (from \$237M to \$242M). However, as explained by Metni et al. (2004), the GB underlying Beirut is highly vulnerable to contamination due to its shallow depth to the water table and karstic geology. The sensitivity of the aquifer to contamination from augmentation with nonpotable water may be of greater concern than the sensitivity of the objective function to changing maximum quantities of aquifer recharge. Unfortunately, little is known about the quality of the GB and an assessment of its response to nonpotable augmentation was outside the scope of this work.

Nonpotable aquifer recharge, in addition to increasing the sustainable yield of Greater Beirut's GB, could protect the aquifer from seawater intrusion. Development of a seawater intrusion barrier may be the principal motivation for future nonpotable aquifer recharge in Lebanon (Mutaseem El-Fadel, personal communication, July 2005). However, this study did not attempt to quantify those or any other ancillary benefits of nonpotable indirect reuse. It seems advisable, given the substantial benefits to be

gained by relaxing the aquifer recharge regulations, that Beirut explore this option. Furthermore, given the similarity in total costs across scenarios presented in Table 4, the writers recommend careful consideration of the environmental implications of water system design choices. Such careful consideration would likely make even more attractive the adoption of wastewater reclamation and source augmentation.

Conclusions

An integrated linear deterministic optimization model was applied to Beirut, Lebanon to determine the minimum cost configuration of future water supply, wastewater disposal, and reuse options for a semiarid coastal city. Two innovations of our work include incorporation of the entire anthropogenic water cycle including interconnections between supply, demand, disposal, and reuse and modeling of the suitability of nonpotable and potable qualities of water for each demand sector. The optimization model yields surprising insights. For example, after full use of inexpensive conventional sources, nonpotable direct reuse appears to be Beirut's most cost-effective option for supply of its urban nonpotable and irrigation demands. Our work highlights the importance of modeling the utility of multiple qualities of water in modern water supply planning.

There is a perception that desalination could soon be a panacea for all of Beirut's water woes. Our results suggest that reclamation and reuse may be more cost-effective than desalination for supply of nonpotable water for urban nonpotable uses, and agricultural irrigation, even if the cost of desalination continues to fall. Previous urban water system optimization models considered only a single quality of potable water and were thus unable to demonstrate the cost-effectiveness of reclaimed water among all viable options for urban water supply.

Since this was the first application of an integrated water supply and wastewater management model based on optimization methods, it should be tested in other semiarid regions. Additions to our model formulation might include more explicit environmental instream flow constraints, blending of water of various qualities, and integration of water and wastewater management with other urban and semiurban water resource challenges such as nonpoint source pollution, local flooding and drainage problems, and lack of access to water-based recreational activities. If social and environmental benefits were quantified then a net benefit formulation could be employed. The model could also be used to develop a Pareto frontier enabling an examination of the optimal trade-offs between human appropriation and environmental allocation of water in coastal cities throughout the developing world.

Sources of uncertainty are found at nearly every stage of this analysis (including model and parameter uncertainty), though an uncertainty analysis was outside the scope of this study. Marginal cost values are useful for sensitivity analyses but are inadequate as a basis for a comprehensive uncertainty analysis. We expect subsequent research to develop a methodology for comprehensive uncertainty analysis of complex linear systems.

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Appendix

Objective Function

$$Z = \left[\begin{aligned} & \sum_s \sum_{gs} \sum_u \sum_{gu} \sum_{ts} fsom_{s,gs} \cdot cs_{s,gs,u,gu} \cdot Qs_{s,gs,u,gu,ts} \\ & + \sum_u \sum_{gu} \sum_w \sum_{ts} fwom_w \cdot cw_{u,gu,w} \cdot (1 - fws_l_w) \cdot Qw_{u,gu,w,ts} \\ & + \sum_r \sum_{gr} \sum_u \sum_{gu} \sum_{ts} from_{r,gr} \cdot cr_{r,gr,u,gu} \cdot (1 - frsl_u) \cdot Qr_{r,gr,u,gu,ts} \\ & + \sum_s \sum_{ts} fxom_s \cdot cx_s \cdot Qx_{s,ts} + fnpdsom \cdot cnpds \cdot \sum_s \sum_u \sum_{gu} \sum_{ts} Qs_{s,N,u,gu,ts}^* \end{aligned} \right] \cdot days_{ts} \\ + \left[\begin{aligned} & \sum_s \sum_{gs} (1 - fsom_{s,gs}) \cdot cs_{s,gs,MU,N} \cdot Qs \max_{s,gs} \\ & + \sum_w (1 - fwom_w) \cdot cw_{MU,N,w} \cdot Qw \max_w \\ & + \sum_r \sum_{gr} (1 - from_{r,gr}) \cdot cr_{r,P,r,gr} \cdot (1 - frsl_r) \cdot Qr \max_{r,gr} \\ & + (1 - fnpdsom) \cdot cnpds \cdot Q \max npds \end{aligned} \right] \cdot 365 \frac{\text{days}}{\text{year}} \quad (1)$$

Conservation of Volume on Each Grade of Use in Each Sector in Each Season (m^3/day)

$$\sum_s \sum_{gs} [(1 - fdsl_{s,gs}) \cdot Qs_{s,gs,u,gu,ts}] + \sum_{gr} [(1 - frsl_u) \cdot Qr_{u,gr,u,gu,ts}] \\ = \sum_w Qw_{u,gu,w,ts} + \sum_{gr} Qr_{u,gu,u,gr,ts} \quad \forall u, gu, ts \quad (2)$$

Consumption in Each Sector in Each Season (m^3/day)

$$Qw_{u,gu,CL,ts} = fcl_{u,gu,ts} \cdot \left(\sum_s \sum_{gs} [(1 - fdsl_{s,gs}) \cdot Qs_{s,gs,u,gu,ts}] \right. \\ \left. + \sum_{gr} [(1 - frsl_u) \cdot Qr_{u,gr,u,gu,ts}] \right) \quad \forall u, gu, ts \quad (3)$$

Physical and Technological Limitation on Recycle (m^3/day)

$$\sum_{gr} Qr_{u,gu,u,gr,ts} \leq frecyc_{u,gu,ts} \cdot \left[\sum_s \sum_{gs} [(1 - fdsl_{s,gs}) \cdot Qs_{s,gs,u,gu,ts}] \right. \\ \left. + \sum_{gr} [(1 - frsl_u) \cdot Qr_{u,gr,u,gu,ts}] \right] \\ - Qw_{u,gu,CL,ts} \quad \forall u, gu, ts \quad (4)$$

Observe Supply Limit at Each Source in Each Season (m^3/day)

$$\sum_{gs} \sum_u \sum_{gu} (Qs_{s,gs,u,gu,ts}) \leq q \max_{s,ts} + baug_s \cdot freuse_s \\ \cdot (1 - fxsl_s) \cdot Qx_{s,ts} \quad \forall s, ts \quad (5)$$

$$\sum_{gs} \sum_u \sum_{gu} Qs_{GA,gs,u,gu,ts} \leq q \max_{GA,ts} + baug_{GA} \cdot freuse_{GA} \\ \cdot (1 - fxsl_{GA}) \cdot Qx_{GA,ts} \\ + \sum_{gu} freuse_{GA} \cdot (1 - fcsl_{GA}) \\ \cdot Qw_{AG,gu,GA,ts-n(ts)} \quad \forall ts \quad (6)$$

$$\sum_{gs} \sum_u \sum_{gu} Qs_{GB,gs,u,gu,ts} \leq q \max_{GB,ts} + baug_{GB} \cdot freuse_{GB} \\ \cdot (1 - fxsl_{GB}) \cdot Qx_{GB,ts} \\ + \sum_{u} \sum_{gu} freuse_{GB} \cdot (1 - fcsl_{GB}) \\ \cdot Qw_{u,gu,GB,ts-n(ts)} \quad \forall ts \quad (7)$$

$$\sum_u \sum_{gu} (1 - f_{csl_{GA}}) \cdot Q_{w_{u,gu,GA,ts}} + (1 - f_{xsl_{GA}}) \cdot Q_{x_{GA,ts}} \leq 2 \cdot q \max_{GA,ts} \quad \forall ts \quad (8)$$

$$\sum_u \sum_{gu} (1 - f_{csl_{GB}}) \cdot Q_{w_{u,gu,GB,ts}} + (1 - f_{xsl_{GB}}) \cdot Q_{x_{GB,ts}} \leq 2 \cdot q \max_{GB,ts} \quad \forall ts \quad (9)$$

$$\sum_{gs} \sum_u \sum_{gu} Q_{s_{WW,gs,u,gu,ts}} + \sum_s baug_s \cdot Q_{x_s} \leq q \max_{WW} + \sum_u \sum_{gu} freuse_{WW} \cdot (1 - f_{csl_{WW}}) \cdot Q_{w_{u,gu,WW,ts}} \quad \forall ts \quad (10)$$

Satisfy Demand for Each Grade of Water at Each Sector in Each Season (m^3/day)

$$\sum_s \sum_{gs} [(1 - f_{dsl_{s,gs}}) \cdot Q_{s_{s,gs,u,N,ts}}] + \sum_{gr} [(1 - f_{tsl_u}) \cdot Q_{r_{u,gr,u,N,ts}}] = fg_{u,N,ts} \cdot q \min_{u,ts} \quad \forall u, ts \quad (11)$$

$$\sum_s \sum_{gs} [(1 - f_{dsl_{s,gs}}) \cdot Q_{s_{s,gs,u,P,ts}}] + \sum_{gr} [(1 - f_{tsl_u}) \cdot Q_{r_{u,gr,u,P,ts}}] = fg_{u,P,ts} \cdot q \min_{u,ts} \quad \forall u, ts \quad (12)$$

Constraints on Construction of New Facilities

$$\sum_{gs} \sum_u \sum_{gu} Q_{s_{DS,gs,u,gu,ts}} \leq Q \max_{DS,P} \quad \forall ts \quad (13)$$

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