Integrated Management of Non-conventional Water Resources in Anhydrous Islands

Songsong Liu · Lazaros G. Papageorgiou · Petros Gikas

Abstract Anhydrous islands are dependent either on non-conventional water resources, such as desalinated seawater or reclaimed water from wastewater, or on water importation from the mainland. The latter option is often expensive and non-sustainable. Desalinated water can be used for potable and non-potable water applications, while reclaimed water can be used for non-potable water applications. Thus all water needs can be satisfied by an optimal blend of desalinated and reclaimed water. It is important to calculate the optimal capacities and locations of seawater desalination plants, wastewater treatment plants and water reclamation plants, and to estimate the water/wastewater conveyance system, in order to minimise water production and distribution costs. Mathematical modelling and optimisation techniques can be employed for calculating the optimum scenario: the satisfaction of all water needs at minimum cost. In this article, we have estimated the water demands taking into account water quality for the anhydrous Greek island of Syros, in the Aegean Sea. Syros has been subdivided into 6 regions, taking into account geographical and population distribution criteria. All water needs are to be satisfied by desalinated seawater and reclaimed water. A mixed-integer linear programming algorithm is used here to calculate the optimal scenario (location and capacities of desalination plants and wastewater treatment and water reclamation plants, as well as the desalinated water, reclaimed water and wastewater conveyance infrastructure needed) by minimising the annualised total cost including capital and operating costs.

Keywords Water resources management · Optimisation · Mixed-integer linear programming · Desalination · Wastewater treatment · Reclamation

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1 Introduction

In geographically isolated areas, like islands, there are few alternative options for water management (Lazarova et al. 2001). In anhydrous islands, groundwater is often non-existent or limited and of poor quality, thus it is often not sufficient to cover the increased water demands (White et al. 2007). Fresh water importation from the mainland is an expensive and non-sustainable option (Gikas and Tchobanoglous 2009b). Thus, it is important to consider non-conventional water resources in water management strategies (Gikas and Angelakis 2009). Water conservation (Bakir 2001) and runoff utilisation should be the top priority in any sustainable water resources management plan. However, the former is unable to solve entirely the problem, while the latter may be expensive, time-consuming, and may also demand valuable land if artificial lagoons are to be constructed. Desalinated seawater (Khawaji et al. 2008) or brackish water (Jaber and Ahmed 2004) and reclaimed water from wastewater (Kalavrouziotis and Apostolopoulos 2007) are the alternative options which may be considered.

Desalinated water is of potable quality and may be used for any potable or non-potable application. Although existing technologies are mature and capable of producing potable water from wastewater (Law 2003), it may be too expensive and may unacceptable by the public for potable uses. Desalinated and reclaimed water should be used in a synergic way and may not been seen as antagonistic products. Reclaimed water can be used for all the non-potable applications in relation to its qualitative characteristics (World Health Organization 2006). Thus, forestry or agricultural applications often require lower quality of reclaimed water compared with landscape or toilet and urinal flushing. A number of factors should be considered in deciding for the optimal blend of desalinated and reclaimed water in order to minimise the total cost, including the follows:

(a)   water quality required;
(b)   technology used for water desalination or reclamation;
(c)   plant location and capacity;
(d)   main and local distribution network;
(e)   storage facilities;
(f)   pumping cost ;
(g)   operational and maintenance costs;
(h)   local constraints and regulations.

Gikas and Tchobanoglous (2009b) have estimated the cost of desalinated and reclaimed water for the islands of the Aegean Sea in Greece, as a function of plant capacity and reclaimed water quality. They have reported a significant dependence of the above cost on the plant capacity. Reclaimed water storage facilities and distribution network may have a significant contribution on the cost of reclaimed water. However, in most islands water demand often follows the pattern of wastewater production, which can contribute in the reduction of storage capacity, a particularly expensive process (Gikas and Tchobanoglous 2009b). It is thus important to estimate the local water demand with the associated measure of quality with relative accuracy in order to calculate the optimal water production and distribution networks. Published work has indicated that decentralized and satellite strategies in water resources management can be particularly beneficial in achieving optimal management (Gikas and Tchobanoglous 2009a). However, if reclaimed water is to be used, a dual distribution system should be established (Okun 1997).

Optimisation techniques can serve as a valuable tool in determining the optimal blend of situations for achieving minimum cost solutions, while satisfying water demands. The model may take into account the existing infrastructure, if any, and can calculate the optimal solution from ground basis. In recent years, optimisation techniques have widely been used in the field of water resource management. Georgopoulou et al. (2001) used dynamic programming to develop a decision aid tool to investigate the feasibility and applicability of an alternative water supply strategy: the desalination of brackish water pumped from aquifers coupled with recharge by treated wastewater. Wang and Jamieson (2002) presented an objective approach to regional wastewater treatment planning based on the combined use of Genetic Algorithm (GA) and Artificial Neural Networks (ANN), to minimise the total cost (capital and operating) of wastewater treatment. Draper et al. (2003) presented an economic-engineering optimisation model for California's major water supply system. Later, Medellín-Azuara et al. (2007) applied the same economic model to explore and integrate water management alternatives within the town of Ensenada, Mexico. Leitão et al. (2005) developed a decision support optimisation model to trace and locate regional wastewater systems, based on Geographic Information Systems (GIS) and location models. Assimacopoulos (2006) presented the evaluation of different scenarios regarding the allocation of water resources and financial, environmental and resource costs for the island of Paros in Greece, based on Decision Support System. Zechman and Ranjithan (2007) applied an extended evolutionary algorithm to generate alternatives (EAGA) to a regional wastewater treatment network design problem. Han et al. (2008) presented a multi-objective linear programming model to allocate various water resources among multiuser and applied it to obtain the reasonable allocation of water supply and demand for Dalian, China. This work was later extended by incorporating uncertain factors in the proposed model and developing an interactive solution approach (Han et al. 2011). Joksimovic et al. (2008) developed decision support software (DSS) for water treatment for reuse with network distribution, in which a GA approach is used for the best selection of customers. Cunha et al. (2009) presented an optimisation model for regional wastewater systems planning, and a simulated annealing (SA) algorithm to optimise the wastewater system of a region. Li et al. (2009) developed an inexact multistage joint-probabilistic programming (IMJP) method for the water resources management with uncertainties within a multi-stream, multi-reservoir and multi-period context with facility by mixed-integer linear programming (MILP) techniques. Liu et al. (2010) presented an optimisation model for the water resources allocation in saltwater intrusion areas, with three objectives: economic interest, social satisfaction and polluted water amounts. The GA approach was used to solve the model, which was applied to the Pearl River Delta in China.

The present work aims to propose an optimisation model approach using MILP techniques to optimise water resources management for Syros, a Greek island of the Aegean Sea (Fig. 1a). The remainder of this paper is organised as follows. The case study of the integrated water resources management on Syros island is described in Section 2. The proposed MILP mathematical model is presented in Section 3. In Section 4, the computational results from applying the proposed model to the case study are given. Then three alternative scenarios are investigated in Section 5. Finally, some concluding remarks are made.

2 Problem Description

Syros, like most of the other small and medium size Aegean islands, undergoes severe water deficiency problems. The potable needs are almost exclusively satisfied by
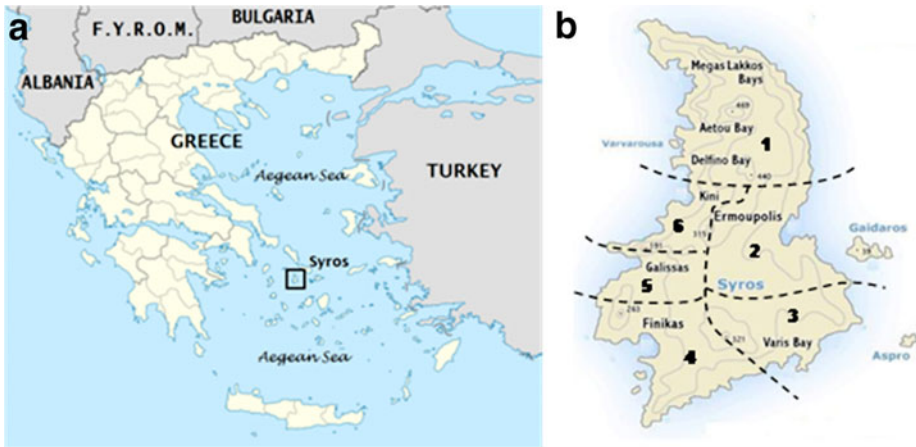
Fig. 1 a The location of Syros island in the Aegean Sea, b Subdivision of Syros island into 6 regions

desalinated seawater. Potable water is also used for the irrigation of private and public landscaping. Groundwater is of limited quantity, with relatively high salinity, and is used almost exclusively as irrigational water for agricultural applications. However, it is not enough to cover all agricultural applications on the island. Wastewater which is produced in the capital and surroundings is treated in a wastewater treatment plant (primary and secondary treatment), while the treated wastewater is disposed into the sea. The treated wastewater cannot be reused as it is produced, as it does not fulfills the water reuse quality criteria. The rest of the island lacks sewerage collection system, as most of the houses are served by cesspits (with a minor exception in a small village). There are no facilities on the island to further process the treated wastewater, as no water reclamation plants are installed. Water demands are significantly increased during the warm months, due to the tourist industry.

This paper aims for the optimal infrastructure on the island with the satisfaction of all water demands and wastewater treatment, at the minimal cost. The infrastructure will include seawater desalination plants, wastewater treatment plants, water reclamation plants, water storage facilities, water and wastewater conveyance systems (including pumping stations). The only available water resources that are considered here are desalinated seawater and reclaimed water from wastewater. Groundwater is not considered, as it is of low quality and of limited quantity, and in any case it is used solely for agricultural applications. Water importation from the mainland is also not considered, as this is a non-sustainable and expensive practice (Gikas and Tchobanoglous 2009b). For methodological purposes, water needs have been classified into four categories: (i) potable water, (ii) agricultural water (in addition to the existing groundwater), (iii) landscape irrigation water, (iv) industrial water. Potable water (i) comes exclusively from desalinated seawater, while all the other needs can be served by either desalinated or reclaimed water.

To estimate the optimal infrastructure for Syros island, with respect to the placement of seawater desalination plants, wastewater treatment plants and water reclamation plants, as well as the water/wastewater conveyance systems and water storage facilities, the island is subdivided into several regions. The establishment of the regions has been based on population distribution on the island and on geographical criteria, trying to assign one main settlement in each region. In the present work, Syros island has been subdivided into six regions (Fig. 1b). The main settlement in each region is at sea level, except for region R1

which is at elevation of 250 m. The "distances", "pumping distances" and "pumping elevations" (for definitions of the terms see Fig. 2) between the main settlements of each couple of regions that water or wastewater distribution is meaningful are given in Table 1.

The daily water demand for each region has been estimated, and has been classified into five categories, as explained above. Potable water comes exclusively from desalinated seawater, while all other needs may be satisfied by either reclaimed or desalinated water. Water demand and wastewater production vary with seasons; with high values occurring during summer and lower during winter. Estimated values of seasonal water demand and wastewater production are shown in Table 2. Here are considered two distinct values: high daily volumes which last for 4 months (June–September) and low daily volumes, which last for the rest 8 months. A more detailed monthly pattern may be used, if more accurate data are available.

In this work, water resources management optimisation problem is calculated on ground basis (the existing infrastructure is not taken into account). The following data are given:

- regions (as described in Fig. 1b);
- pairwise distances of the relative population centers of the regions and elevations (see Fig. 2 and Table 1);
- potable and non-potable water demands and wastewater productions in each region (see Table 2);
- volume costs of desalinated seawater and reclaimed water production (additional treatment following wastewater treatment), and wastewater treatment, as a function of plant capacity, which includes all the associated costs (capital and operational including energy, using the calculation methodology proposed by Gikas and Tchobanoglous 2009b) (see Table 3)
- costs of pipelines (installed), as a function of pipeline length and pipe diameter (see Table 4);
- cost of steel storage tanks, as a function of storage capacity (2 days storage at high demand season);
- types and costs of pumping stations(see Table 5);
- unit cost of electric power (produced by a mixture of diesel engines and wind power);
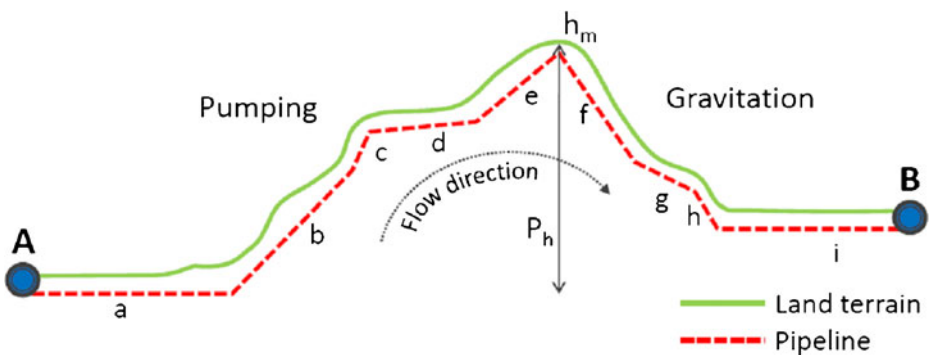
Fig. 2 Schematic graph for the definition of the terms: "distance", "pumping distance" and "pumping elevation" between points "A" and "B", for flow direction A→B: The length of the pipeline between A and B is called "distance" = a+b+c+d+e+f+g+h+i, the length of the pressurized pipeline is called "pumping distance" = a+b+c+d+e, the maximum height that the liquid has to be pumped is called "pumping elevation" = P_h

Table 1 Distances/pumping distances/pumping elevations between the main settlements of two regions (km)

	R1	R2	R3	R4	R5	R6
R1		8/0/0	×	×	×	3.3/0/0
R2	8/8/0.25		5.2/2.3/0.12	9/3.3/0.15	7.3/4/0.18	5.3/3.7/0.26
R3	×	5.2/2.9/0.12		5.3/2/0.02	×	×
R4	×	9/5.7/0.15	5.3/3.3/0.02		5.7/3.7/0.05	×
R5	×	7.3/3.3/0.18	×	5.7/2/0.05		4.2/1.7/0.12
R6	3.3/3.3/0.25	5.3/1.6/0.26	×	×	4.2/2.5/0.12	

×: The direct link between these regions is *a priori* not allowed

to determine:

- allocations and capacities of desalination, wastewater treatment and reclamation plants;
- pipeline main network for desalinated seawater, wastewater and reclaimed water, including piping diameters (local piping network is not considered);
- daily volumes of desalinated seawater, wastewater and reclaimed water production;
- main flows of desalinated seawater, wastewater and reclaimed water between the regions;
- number, types and operation time of pumps for each established link;

so as to minimise the annualised total cost, including capital cost and operating and maintenance (O&M) cost. The cost of the local water distribution system and local wastewater collection system within each region is not considered here.

3 Mathematical Model

The proposed model is to obtain the optimal infrastructure (minimum capital and operating and maintenance costs), which satisfies all needs for water demand on the island, taking into account water quality demands and seasonal needs. Thus, the model suggests the optimal location and capacity of seawater desalination plants, wastewater treatment plants and water reclamation plants, the capacities and locations of water storage facilities (for both desalinated and reclaimed water) and the potable water, non-potable water and wastewater mains conveyance system and pumping stations. Both qualities of water and wastewater are allowed to be freely distributed along most of the regions (see Table 1), in order to satisfy all the water needs, at minimum cost.

Table 2 Estimated water demands and wastewater production in Syros

		Volume per day (summer/winter) (m^3/day)					
		R1	R2	R3	R4	R5	R6
Potable water demand		150/50	4,000/2,800	500/250	650/350	500/200	500/300
Non-portable water demand	Agricultural	100/0	200/0	400/0	700/0	400/0	200/0
	Landscape	150/0	600/0	150/0	150/0	150/0	150/0
	Industrial	0/0	100/100	50/50	30/30	30/30	30/30
	Total	250/0	900/100	600/50	880/30	580/30	380/30
Wastewater production		150/50	3,700/2,600	200/100	300/150	300/150	450/250

Table 3 Unit costs of desalinated seawater and reclaimed water production and wastewater treatment (US\$/m^3)[a]

Volumetric capacity (m^3/day)	Desalinated seawater	Wastewater	Reclaimed water[b]
50–1,000	2.5	0.34	0.30
1,000–2,500	1.5	0.24	0.18
2,500–5,000	1.0	0.19	0.17
5,000–10,000	0.8	0.17	0.16

[a] Adapted in part from Gikas and Tchobanoglous (2009b)

[b] Additional cost following standard wastewater treatment

3.1 Objective Function

The objective of the proposed model is to minimise the annualised total cost, which can be expressed as the summation of the annualised capital cost and annualised operating & maintenance cost (including energy cost). To calculate the annualised capital cost, the total capital cost is multiplied by the Capital Recovery Factor (CRF) (Gillot et al. 1999; Xu et al. 2001), which is equal to 0.08 (corresponding to 5% interest rate and a project life of 20 years).

The production cost of desalinated seawater, reclaimed water and treatment cost of wastewater includes capital, depreciation, energy cost, and O&M cost, as a function of plant capacity. Table 3 gives the unit cost used in the present work (per cubic meter of water or wastewater).

Apart from the above production costs, the capital costs include the pipeline capital cost, pumping station capital cost and storage capital cost. The unit cost of the installed pipelines, as function of pipe diameter is given in Table 4 (Gikas and Tchobanoglous 2009b). Similar types of plastic pipes have been accounted for water and wastewater conveyance. The cost of pumps, as a function of pump capacity, is given in Table 5. The cost of pumps also depends on the type of pumping liquid, thus pumps for wastewater are more expensive, compared to those for water. Moreover, we consider that water may be pumped up to 400 m using a single pump, while wastewater may be pumped up to 50 m (because of the relatively higher solids content). If water or wastewater has to be pumped at greater elevations, additional pumping stations are needed. Each pumping station consists of a pair of pumps (operating and stand by); it has been assumed that the shell of each pumping station costs US\$11,000. Water storage facilities, made of steel, with retention time of 2 days (high demand) are assumed at a unit cost of US\$500/m^3 of tank volume (Gikas and Tchobanoglous 2009b).

The operating pumping cost is a function of the pumping elevation P_h, head losses and unit electricity cost (US\$0.15/kWh). The head losses have been calculated by the Hazen–Williams Equation, in which the flow rates are calculated based on pipe diameters (see Table 4) and water/wastewater velocities. Here we have assumed that the pumps operate at constant flow, to yield velocities of 0.8 m/s and 1.0 m/s, for water and wastewater, respectively. Thus to achieve a smaller cumulative daily flow rate, the pumps will have to operate, on and off, for a fraction of the day. The roughness constant used for plastic pipes

Table 4 Unit costs of installed pipes, as a function of pipe diameter[a]

Pipe diameter (in)	2.5	4	6	10
Pipeline cost (installed) (US\$/m)	55	60	65	70

[a] Adapted from Gikas and Tchobanoglous (2009b)

Table 5 Flow rates, costs and maximum pumping elevations of water/wastewater pumps

Flow rate (m³/day)		240	720	1,200	2,400
Water pump	Pump cost (US$)	5,000	10,000	14,000	19,000
	Maximum pumping elevation (m)	400	400	400	400
Wastewater pump	Pump cost (US$)	6,000	19,000	28,000	56,000
	Maximum pumping elevation (m)	50	50	50	50

has been taken equal to 150 (Brière 2007). To establish a relationship between the flow rates and the actual flows in 1 day, a positive variable γ_{klt} ($0 \leq \gamma_{klt} \leq 1$) is introduced to represent the proportion of operation time in a day.

3.2 Allocations and Mass Balance Considerations

To model the plant productions, water/wastewater flows and pipeline network, the following notations are introduced:

Indices

k, l region
m piecewise function interval
p pipe type
t season

Sets

SO_l^{dw}/SI_l^{dw} set of possible sources/sinks of desalinated seawater to/from region l
SO_l^{ww}/SI_l^{ww} set of possible sources/sinks of wastewater to/from region l
SO_l^{rw}/SI_l^{rw} set of possible sources/sinks of reclaimed water to/from region l

Parameters

D_{lt}^{p} demand of potable water in region l during season t, m³/day
D_{lt}^{np} demand of non-potable water in region l during season t, m³/day
S_{lt}^{ww} wastewater production in region l during season t, m³/day
M_m^{L} lower ends of the interval m, m³/day
M_m^{U} upper ends of the interval m, m³/day

Continuous Variables

O_{lt}^{dr} flow of desalinated seawater to reclaimed water system in region l during season t, m³/day
P_{lt}^{dw} total desalinated seawater production in region l during season t, m³/day
$\tilde{P}_{ltm}^{dw}$ desalinated seawater production within interval m in region l during season t, m³/day
Q_{klt}^{dw} flow of desalinated seawater from region k to l during season t, m³/day
Q_{klt}^{rw} flow of reclaimed water from region k to l during season t, m³/day
Q_{klt}^{ww} flow of wastewater from region k to l during season t, m³/day
W_{lt}^{rw} reclaimed water production in region l during season t, m³/day
W_{it}^{sw} wastewater amount discharged to the sea in region l during season t, m³/day
W_{lt}^{ww} treated wastewater production within region l during season t, m³/day

Binary Variables

X_{ltm}^{dw} 1 if daily production of desalination plant in region l during season t lies within interval m

Y_{klp}^{dw} 1 if type p is selected to be used as the pipeline of desalinated seawater from region k to l

Figure 3 shows the possible water (desalinated and reclaimed) and wastewater flows for region l. In region l and during season t, the desalinated seawater production amount, plus all incoming desalinated water flows, should be equal to the potable water demands, plus outgoing flows to other regions and to local reclaimed water system:

$$\sum_{k \in SO_l^{dw}} Q_{klt}^{dw} + P_{lt}^{dw} = \sum_{k \in SI_l^{dw}} Q_{lkt}^{dw} + O_{lt}^{dr} + D_{lt}^{p}, \qquad \forall l, t \tag{1}$$

From Table 3, the unit cost of desalinated water is a piecewise function. For each operating plant during each season, the volume of water produced should lie in at most one interval:

$$\sum_m X_{ltm}^{dw} \leq 1, \qquad \forall l, t \tag{2}$$

It should be noted that if (for any reason) desalination plant is not allowed to be installed in region l, the right hand side of the above equation should be replaced by 0.

If interval m is selected, the daily water volume production in this interval should be limited by the bounds of the interval; if an interval is not selected, the production in this interval should be 0:

$$M_m^L \cdot X_{ltm}^{dw} \leq \widetilde{P}_{ltm}^{dw} \leq M_m^U \cdot X_{ltm}^{dw}, \qquad \forall m, l, t \tag{3}$$

As there is at most one interval in which the production can be positive, the summation of the productions over all intervals should be equal to the production:

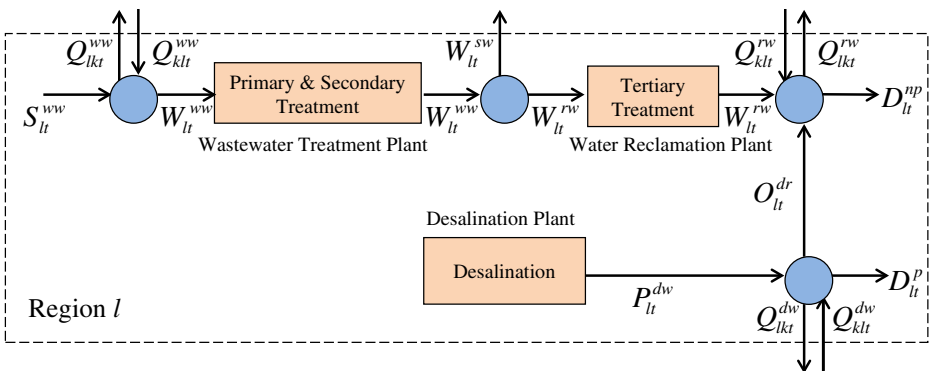$$P_{lt}^{dw} = \sum_m \widetilde{P}_{ltm}^{dw}, \qquad \forall l, t \tag{4}$$

Fig. 3 Schematic graph of wastewater treatment, water reclamation and desalinated seawater production and distribution

In each wastewater treatment plant, all wastewater undergoes primary and secondary treatment. Then part of the treated wastewater is further treated in a tertiary treatment plant, at an extra cost, while the rest is discharged into the sea (Fig. 3). The treated wastewater is the summation of the reclaimed water and the discharged treated wastewater:

$$W_{lt}^{ww} = W_{lt}^{rw} + W_{lt}^{sw}, \qquad \forall l, t \tag{5}$$

If there is a wastewater treatment and reclamation plant in region l, the daily wastewater production plus all incoming wastewater flows should be equal to the summation of the outgoing wastewater flows, and the daily amount of wastewater treated by primary and secondary treatment:

$$\sum_{k \in SO_l^{ww}} Q_{klt}^{ww} + S_{lt}^{ww} = \sum_{k \in SI_l^{ww}} Q_{lkt}^{ww} + W_{lt}^{ww}, \qquad \forall l, t \tag{6}$$

The production of reclaimed water plus the incoming reclaimed water and possibly the desalinated seawater is the summation of the outgoing reclaimed water and the non-potable demands in region l:

$$\sum_{k \in SO_l^{rw}} Q_{klt}^{rw} + O_{lt}^{dr} + W_{lt}^{rw} = \sum_{k \in SI_l^{rw}} Q_{lkt}^{rw} + D_{lt}^{np}, \qquad \forall l, t \tag{7}$$

It should be mentioned that the wastewater treatment and water reclamation costs are also represented by piecewise functions. Thus, similarly to the desalinated water, binary variables and constraints are proposed to model wastewater treatment and water reclamation.

In the pipeline network for desalinated water, for each link, at most one pipe type p can be selected:

$$\sum_p Y_{klp}^{dw} \leq 1, \qquad \forall l, k < l, k \in SO_l^{dw} \tag{8}$$

The pipeline from region k to l is the same one as from region l to k, so Y_{klp}^{dw} and Y_{lkp}^{dw} should always have the same value:

$$Y_{klp}^{dw} = Y_{lkp}^{dw}, \qquad \forall l, k < l, k \in SO_l^{dw}, p \tag{9}$$

Similar binary variables and constraints are also proposed for the pipeline networks for both wastewater and reclaimed water. In summary, the above proposed mathematical model is a mixed-integer linear programming (MILP) model.

4 Computational Results

The model has been implemented in GAMS 22.8 (Brooke et al. 2008), using the solver CPLEX 11.1 (ILOG 2007) for the optimal solution, on an Intel Pentium 4, 3.40 GHz, 1.00 GB RAM machine. The optimality gap is set to 0%. After a CPU time of 412 s, the obtained optimal solution gives an annualised total cost of US$3,146,603/year. In the optimal solution (see Fig. 4), the sole seawater desalination plant is allocated in region R2, while wastewater treatment plants and water reclamation plants are required in every region, which is in agreement with the study of Gikas and Tchobanoglous (2009a), arguing about the benefits of decentralized water management. It should be noted that the optimal solution indicates that all wastewater should be treated in the region where it is produced,
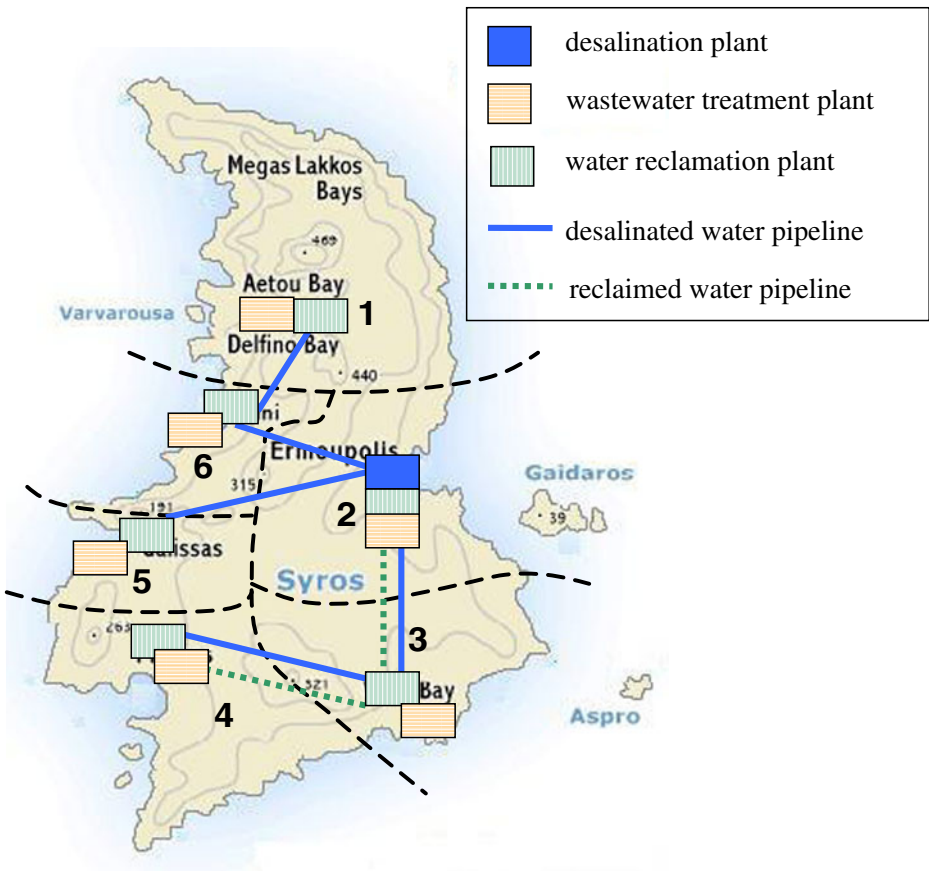
Fig. 4 Optimal plant allocations and pipeline networks

thus there is no need for wastewater distribution around the regions. The details of the optimal solution are shown in Table 6, including information for each established link

Table 6 Model predictions for each established link

| Link	Water type[a]	Pipe diameter (in)	Flow rate (m³/day)	Direction	Pump capacity (m³/day)	Pump No. (operating)	Daily fraction of operation time	
							Summer	Winter
1–6	dw	4	560.4	6→1	720	1	0.45	0.09
2–3	dw	6	1260.9	2→3	2,400	1	0.93	0.48
2–5	dw	6	1260.9	2→5	2,400	1	0.62	0.18
2–6	dw	6	1260.9	2→6	2,400	1	0.60	0.30
3–4	dw	6	1260.9	3→4	2,400	1	0.53	0.28
2–3	rw	6	1260.9	2→3	2,400	1	0.92	0
3–4	rw	4	560.4	3→4	720	1	1	0.05

[a] *dw* desalinated water, *rw* reclaimed water

(flow/direction, type and number of pump stations, operation time proportion in a day (γ_{klt})
of pumps for each season).

As mentioned above, the model gives the total cost of US$3,146,603/year, whose
breakdown is given in Fig. 5. From Fig. 5, it can be seen that the cost for the production of
desalinated water is about 51.7% of the total cost, while water storage facilities account for
about 25.2%. The combined cost of installed pipelines and pumping stations is relatively
small (6.8%), which is probably due to the fact that the optimal solution allocates one
wastewater treatment plant in each region, thus there is no requirement for trans-region
instalment of wastewater conveyance pipelines.

In the optimal solution, the daily production of desalinated seawater in R2 is 6699.6 m^3/day
in summer time and 4,010 m^3/day in winter time. The production of wastewater in each
region is depicted in Fig. 6. Each column of the graph in Fig. 6 shows the amount of disposed
treated wastewater and the amount of treated wastewater which is used for reclamation. The
wastewater treatment plant in R2 processes the greatest amount of wastewater among all
regions (3,700 m^3/day in summer and 2,600 m^3/day in winter).

In the optimal solution, all water demands for every region are satisfied. The non-potable
water demand at each region can be satisfied by a mixture of local reclaimed water (rw local),
local desalinated water (dw local), plus imported reclaimed water (rw imported) and desalinated
water (dw imported) from other regions (Fig. 7). We can see that some quantities of
desalinated water (which is imported from R2) are used to partially cover non-portable
demands in regions R1, R4, R5 and R6. Characteristically, as seen in R4, the non-potable
water demand (880 m^3/day) in summer is satisfied by the local reclaimed water (300 m^3/day),
reclaimed water which is imported from region R2 (560.4 m^3/day), and desalinated water
which is also imported from R2 (19.6 m^3/day). In principle, potable water demand at each
region can be satisfied by local desalinated water production (dw local), and imported
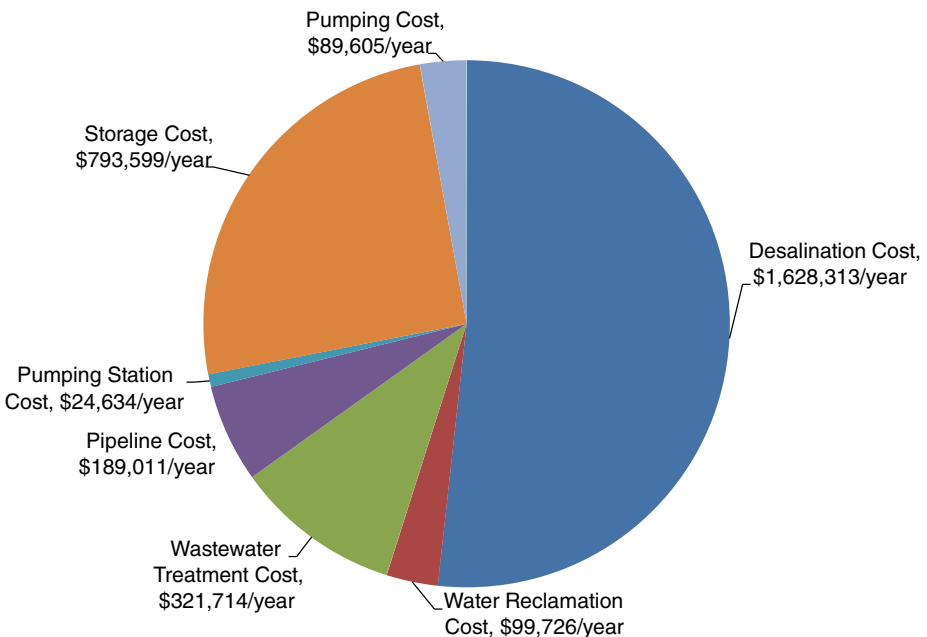
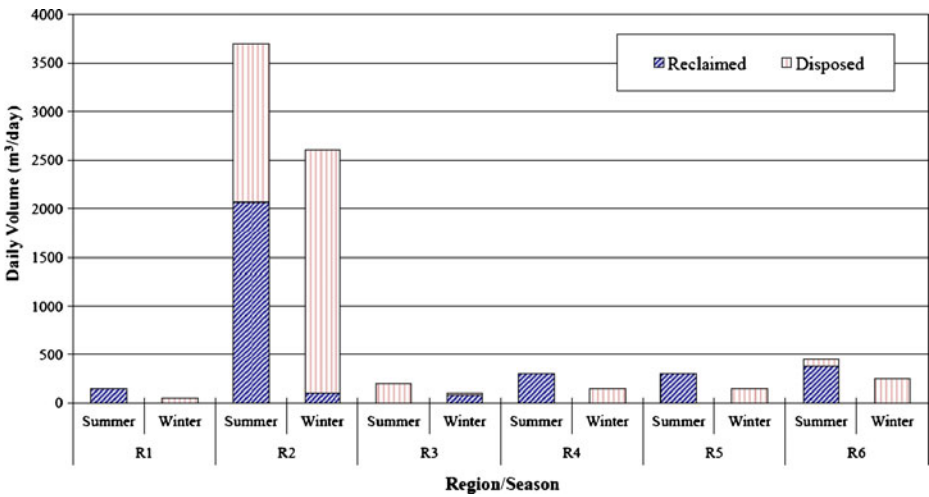Fig. 5 Breakdown of the optimal annualised total cost

Fig. 6 Daily volumes of reclaimed water and disposed treated wastewater by the treatment and reclamation plants

desalinated water from other regions (dw imported). However, the model indicated that all desalinated water should be produced in R2, and then distributed to the other regions (Fig. 8).

5 Sensitivity Analysis

In this section we consider 3 alternative scenarios of the problem, as described below:

1. "Current situation": Currently, every region on the island, except R1, has seawater desalination facilities; the sole wastewater treatment on the island is
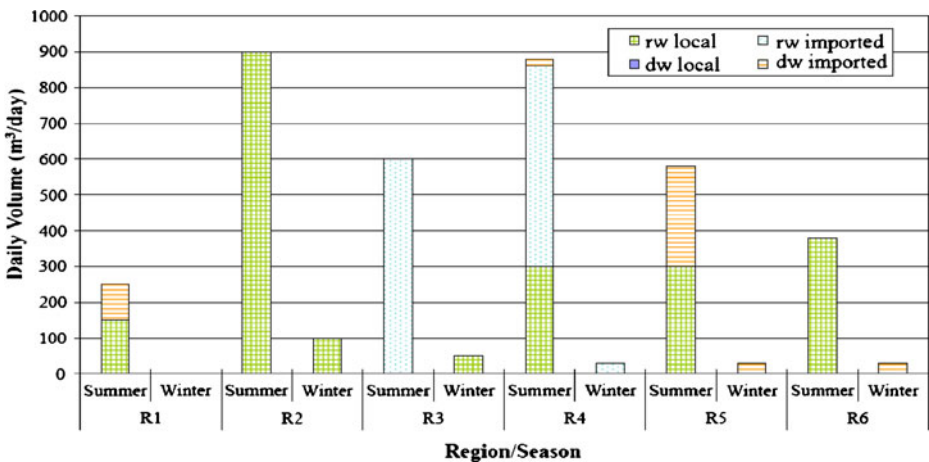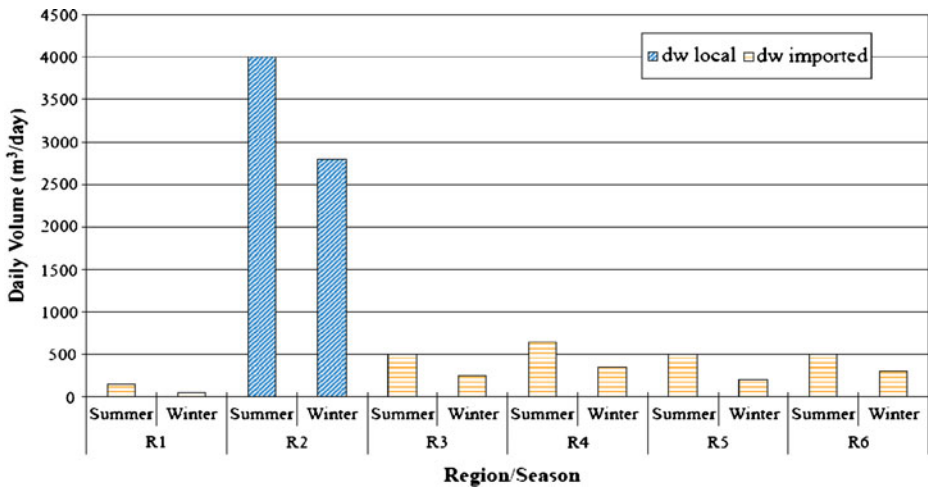

Fig. 7 Daily volumes of non-potable water supply in each region. (rw local: reclaimed water produced in this region; rw imported: reclaimed water conveyed from other regions; dw local: desalinated water used for non-potable applications and produced in this region; dw imported: desalinated water used for non-potable applications and conveyed from other regions)

Fig. 8 Daily volumes of potable water supply in each region. (dw local: desalinated water used for potable applications and produced in this region; dw imported: desalinated water used for potable applications and conveyed from other regions)

located in R2; there are no water reclamation facilities on the island. This scenario calculates the optimal capacities of the facilities at the existing locations (establishment of additional facilities is not allowed) for the minimisation of the overall cost.

2. "No reclamation": This scenario assumes that water reclamation is not practised on the island, thus all water demands (potable and non-potable quality) are satisfied by desalinated seawater, while all wastewater undergoes secondary treatment and disposed into the sea.

3. "No pipeline": This scenario assumes that water or wastewater distribution between the regions is not allowed, thus each region has to satisfy its water needs and wastewater treatment obligations.

The models are implemented in the same environment as the optimal scenario. The optimal plant allocations and pipeline networks are presented in Fig. 9. The optimal objective, the allocations and capacities of the plants in each scenario are given in Table 7. As expected, the annualised total cost of all alternative scenarios is higher to the one calculated for the optimal scenario. If the "current situation" (scenario 1) is used to satisfy all water needs and wastewater treatment obligations, the annualised capital cost is calculated 14.5% higher than the optimal solution. If water reclamation is not practiced on the island (scenario 2), the model indicates that there should be installed 3 seawater desalination plants plus 6 wastewater treatment plants on the island. Scenario 2 is more beneficial than scenario 1 in terms of annualised total cost. The annualised total cost of the "no pipeline" scenario (scenario 3), is the higher than all others. It is approximately 25% higher than the one indicated by the optimal.

6 Conclusions

In this paper, an optimisation model has been proposed for the integrated management of desalinated, reclaimed water and wastewater (for islands lacking other water resources),
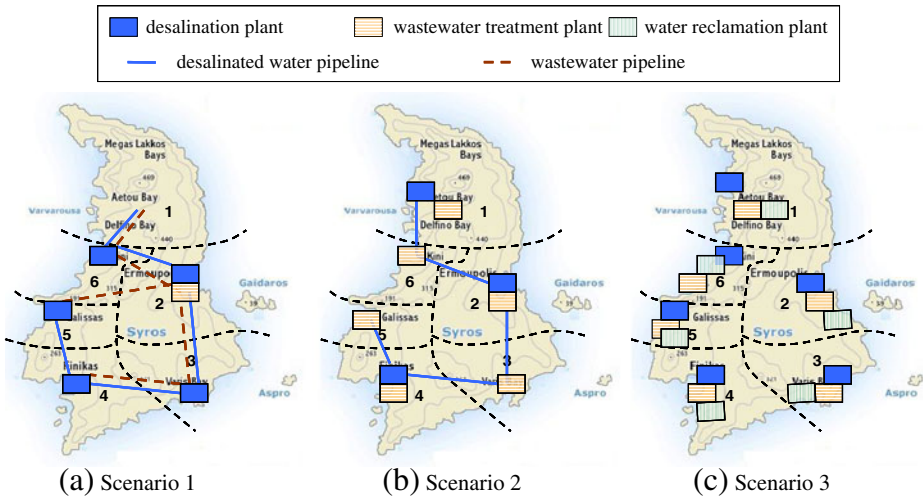
Fig. 9 Optimal plant allocations and pipeline networks in each scenario

with respect to the annualised total cost. The model has been applied to the Greek island of Syros to minimise the annualised total water and wastewater management cost. Based on realistic estimations about water demand (with respect to water quality and seasonal demand) and wastewater production and assuming logical subdivision of Syros island into

Table 7 Computational results (annualised total cost and capacities of allocated plants) of the alternative scenarios

	Optimal solution	Scenario 1	Scenario 2	Scenario 3
Annualised total cost (US$/year)	3,146,603	3,603,655	3,400,958	3,937,694
Allocation of desalination plants (capacity in m³/day)	R2 (6,700)	R2 (7,240)	R1 (50)	R1 (250)
		R3 (50)	R2 (7,340)	R2 (4,000)
		R4 (2,500)	R4 (2,500)	R3 (1,000)
		R5 (50)		R4 (1,230)
		R6 (50)		R5 (1,000)
				R6 (500)
Allocation of wastewater treatment plants (capacity in m³/day)	R1 (150)	R2 (5,100)	R1 (150)	R1 (150)
	R2 (3,700)		R2 (3,700)	R2 (3,700)
	R3 (200)		R3 (200)	R3 (200)
	R4 (300)		R4 (300)	R4 (300)
	R5 (300)		R5 (300)	R5 (300)
	R6 (450)		R6 (450)	R6 (450)
Allocation of water reclamation plants (capacity in m³/day)	R1 (150)	None	None	R1 (150)
	R2 (2,060)			R2 (900)
	R3 (80)			R3 (100)
	R4 (300)			R4 (300)
	R5 (300)			R5 (80)
	R6 (380)			R6 (380)

6 regions, the model provides the optimal locations and capacities of seawater desalination, wastewater treatment and water reclamation plants, the optimal water conveyance infrastructure, such as length and diameter of pipelines, and number and types of pumps, by minimising the annualised total cost.

In the sensitivity analysis, we considered three alternative scenarios, including "current situation", "no reclamation" and "no pipeline". Comparing the alternative scenarios with the optimal solutions, we have the following conclusions:

1. The current allocation of the plants is not optimal in term of minimum cost, and can be improved by reducing the number of desalination plants and increasing the number of wastewater treatment and water reclamation plants;
2. Water reclamation can satisfy the non-potable water demand at a lower cost, thus waster reclamation plants should be installed on the island.
3. The optimisation problem should consider the potential interactions between the regions on the island. If distribution is not allowed, and all needs are to be satisfied independently in each region, the annualised total cost can be significantly higher.

It should be noted, that the outcome of the alternative scenarios and the above conclusions are case specific. Thus, a completely different solution may prove ideal for another island, or for the studied island if more accurate data are available.

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