Water management in small islands: an optimisation model for Paros

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Abstract

The current approach aims to assess the margins for the implementation of demand management as an inherent part of the necessary capacity expansion of the water supply system in the island of Paros, Greece. The analysis is conducted through a non-linear optimisation model. The objective is to minimize the net present value of the system costs for a 20 year period subject to constraints that refer to minimum and maximum capacities of alternative options and maximum potential for water conservation measures. The results identify the most appropriate mix of alternative water supply options and demand side measures to meet the projected water demand. Alternative water management scenarios that include demand side measures of different costs are developed and compared to a reference state which adopts only supply side options.

L'approche courante vise à évaluer les marges pour l'exécution de la gestion de demande, comme une partie inhérente de l'expansion nécessaire de la capacité du système d'approvisionnement de l'eau en l'île de Paros, Grèce. L'analyse est conduite par un modèle non linéaire d'optimisation. L'objectif est de réduire au minimum la valeur nette des coûts de système, pendant une période de 20 ans. Les contraintes se rapportent aux capacités minimum et maximum des options alternatives, et potentiel maximum pour des mesures de conservation de l'eau. Les résultats identifient la combinaison la plus appropriée des options alternatives pour l'augmentation des ressources disponibles et des mesures de normalisation pour satisfaire la demande projetée. Des scénarios alternatifs de gestion de l'eau, qui incluent des mesures de conservation des différents coûts, sont développés et comparés à un état de référence qui adopte seulement des options qui se limitent à l'approvisionnement de l'eau.

1 Introduction

Water demand management provides the basis for an integrated approach in resources management when natural water resources have been tapped or face significant pressures. Therefore, water supply and demand management have to be simultaneously assessed in a context that takes into account both economic and environmental constraints. Water demand management strategies were first elaborated in the 80s when the physical or financial limits of supply enhancement options became evident. Despite the increasing interest in the subject, few economic analyses of large scale policies exist. Even when the scope of the analysis is more limited, as for example leakage control in a particular distribution network, the economic evaluation is a difficult task due to the complexity of the problems and the different states of distribution networks [1, 2].

Paros is a small typical Greek island, whose economic activities rely mostly on summer tourism. Seasonal population increase creates a serious water shortage problem for one or two months. Groundwater is, in most cases, adequate to cover the local population needs, which however represent only a small fraction of the peak summer demand. The predominant water management practices are restricted to a very limited set of water supply options, such as overexploitation of groundwater resources, desalination and demand management options in the form of extensive water supply quotas and high volumetric water prices. The direct impacts of traditional water management practices are mainly concentrated on seawater intrusion in coastal aquifers and the highly inefficient operation of the water supply system (salt deposits, high operational costs). Moreover, the level of service provision is considered unacceptable for most of the islands due to the extensive supply quotas [3, 4].

Two major assumptions determine the scope of the current analysis which concentrates on the household and hotel sectors; (1) the demand management measures are carried out or financed by the water utility, which is also responsible for the supply capacity expansion and (2) the demand management measures do not affect the level or the cost of services provided to the consumers. Therefore the problem is transformed into the identification of the optimal mix of demand and supply management that minimises the overall water supply costs for the water utility in a planning horizon of 20 years. Towards this end, an optimisation model has been developed for the identification of the least cost combination of water management options and the evaluation of alternative water management scenarios determined by different sets of potential demand management measures. The goal is to specify the level of water demand management that contributes to the financial sustainability of the water supply system.

2 Optimisation Model

An optimisation model for the island of Paros in Greece has been developed and used for the identification of the optimal water management scheme. Simulation models were used for the estimation of the costs and water production from applicable supply side options. Alternative demand management options have been modelled on the basis of their cost and potential for water savings. Available models are integrated in an optimisation model that minimises the total water supply cost for a period of 20 years. The potential contribution of each supply side option is bounded by upper and lower limits, which are defined on the basis of technical and environmental constraints. The optimisation model treats demand side measures as a hypothetical supply option that faces a part of the monthly water demand equal to the water savings achieved. This approach allows for the coherent evaluation of both demand and supply management options through the optimisation model without requiring a new estimation of the water demand.

The objective function is to minimise the net present value of the total annual costs for water supply (Eq. 1). The discount rate has been assumed at 6 % and the period up to 2020 is analysed.

$$Min\left[\sum_{k=1}^{n}\frac{C_k}{(1+r)^k}\right] \quad (1)$$

C_k = Total water supply cost for year k (k= 1 – 20 years)

r = Discount rate

n = Duration of the analysis period in years

The annual costs for each of the solutions examined include both fixed costs that in most cases depend only on the plant capacity and variable costs that depend on the produced water. Equation 2 estimates the total annual water supply cost.

$$C_k = \sum_{i=1}^{12}\sum_{j=1}^{5} AC_{j,i,k} + OM_{j,i,k} \cdot Q_{j,i,k} \quad (2)$$

$AC_{j,i,k}$ = Fixed cost for supply option j, in month i, in year k

$OM_{j,i,k}$ = Variable cost for option j, in month i, in year k

$Q_{j,i,k}$ = Monthly water production from option j, in month i, in year k

Simple models have been developed for: water demand management (*j=1)*, groundwater boreholes (*j=2)*, surface storage reservoir (*j=3)*, desalination (*j=4)* and water hauling (*j=5)* that estimate water production and fixed and variable cost on a monthly basis.

In Eq. 2, $Q_{j,i,k}$ depends on the monthly water demand (since the water supply from all sources should not exceed the water demand). For the estimation of $Q_{j,i,k}$, it has been assumed that alternative options are employed successively, according to ascending costs until the monthly water demand is met. In this case, the simulation models are used to estimate the maximum monthly water available from each option.

Demand management

The monthly water savings from demand management options are estimated using Eq. 3.

$$QM_{1,m} = dsm_i \cdot D_m \qquad (0 \le dsm_i \le dsm_{\max} < 1) \quad (3)$$

$QM_{1,m}$ = Maximum water savings through demand management for period m (m = 1 - 240 months)

dsm_i = water savings through demand management in month i (1=1-12)

D_m = water demand in period m

dsm_{max} = maximum achievable water savings

The lack of extensive data on water savings and costs of particular water conservation measures has been addressed through the modelling of several alternative options. Each option is defined by a different set of costs (OM_1) and maximum water savings and each identified solution determines a different scenario.

Groundwater boreholes

The monthly water production from groundwater boreholes has been estimated according to the current groundwater usage pattern. There are more than 40 boreholes in Paros with a total capacity of 923 m^3/h. During July and August almost all boreholes operate at over 90% of their full capacity, in an effort to follow the increased water demand, while for the rest of the year, near 50% of this capacity is in operation. The current situation in Paros indicates that a slow increase in borehole capacity will not create irreversible problems to groundwater resources. Consequently, an increase of 1% annually is assumed for the next decade and then maintained at this level for the rest of the analysed period. Monthly water production from is modelled by Eq. 4:

$$QM_{2,m} = G \cdot b_i \cdot B \qquad (4)$$

$QM_{2,m}$ = Maximum water production from boreholes for period m

G = Fraction of the total boreholes capacity used

b_i = Fraction of the available boreholes capacity that is in operation in month i

B = Overall capacity of groundwater boreholes

The investment cost for a typical drilling has been estimated on the basis of available data for existing boreholes in Paros at 24,000 €. Water production cost, including fixed and variable costs, is estimated at 0.28 €/m^3.

Surface storage reservoir

The simplified water balance for a surface water storage reservoir is modelled by Eq. 5:

$$V_m = V_{m-1} + I_m - E_m - Q_m \qquad (0 \le V_{mi} \le V_{\max}) \qquad (5)$$

V_m = Available volume of water at the end of period m

V_{max} = Storage capacity of the reservoir

I_m = Water inflows to the reservoir during period m

E_m = Evaporation from the reservoir surface during period m

Q_m = Water abstractions during period m

The above equation refers to the volume of water available for abstraction and does not take into account the dead volume that remains in the reservoir. Reservoir inflows are estimated on the basis of monthly precipitation data and an overall runoff coefficient for the area. It is assumed that when inflow exceeds the storage capacity of the reservoir, excess water is rejected. Evaporation losses are estimated using the average values from similar cases in Greek islands.

Water abstraction is estimated as a fraction of the monthly water demand and cannot exceed the monthly availability of water in the reservoir (Eq 6).

$$QM_{3,m} = \min(V_{m-1}, a_i \cdot D_{3,m}) \qquad (6)$$

$QM_{3,m}$ = Maximum water production from the reservoir for period m

$D_{2,m}$ = Water demand not met by the boreholes in period m

a_i = Fraction of the demand covered by the reservoir in month i ($0 < a_i < 1$)

The investment cost for the storage reservoir is estimated using Eq. 7 and includes construction costs, land acquisition, network construction and water cleaning equipment. Eq. 7 has been derived from exponential interpolation of available cost data from 94 operating storage reservoirs in Greece [8]. Project lifetime is assumed to be 20 years.

$$CC_3 = 1090.8 \cdot (V_{\max})^{0.61} \tag{7}$$

CC_3= Investment cost for a surface storage reservoir

The operational cost includes maintenance and labour costs and has been estimated at 0.16 €/m^3.

Desalination

The monthly water production for a grid powered reverse osmosis desalination plant is determined using Eq. 8:

$$QM_{4,m} = Des \cdot t_m \tag{8}$$

$QM_{4,m}$ = Maximum water production from the reservoir for period m

Des = Daily capacity of the desalination plant

t = Days of plant operation in period m (t=30)

The daily capacity of the RO plant is a decision variable defined by the optimisation model. The upper limit of the conventional desalination capacity that could be installed in the island is assumed at 5,000 m^3/d.

For conventional reverse osmosis plants, the most important components of the investment cost are membrane and electromechanical equipment costs. The capital cost is modelled with Eq. 9, derived through exponential interpolation of cost data collected from operating desalination plants in Greek islands. Plant lifetime is assumed equal to 15 years. It should be noted that plants are replaced at the end of their lifetime.

$$CC_4 = 2270 \cdot (Des)^{0.875} \tag{9}$$

CC_4 = Investment cost for a reverse osmosis plant

Operation and maintenance costs include energy, chemicals, membrane replacement, and labour costs [9]. Energy costs that reach near 60% of the running costs are estimated assuming a specific energy consumption of 5 kWh/m^3. Operational and maintenance costs depend on the capacity of the plant and range from 0.79 - 0.81 €/m^3 for a capacity in the range of 500 – 10,000 m^3/day.

Decision variables and constraints

The decision variables and the relevant constraints for the optimisation problem are:

- Water savings through demand management in month i ($0 \le dsm_i \le dsm_{\max} < 1$)
- Fraction of the total boreholes capacity used ($0 < G < 1$)
- Storage capacity of the reservoir ($0 < V_{max} < 250{,}000$)
- Fraction of the remaining demand covered by the reservoir in month i ($0 < a_i < 1$)
- Daily capacity of the desalination plant ($0 < Des < 5{,}000$)

3 Context of analysis

Water demand management generally refers to a wide set of policies, measures and interventions with the objective to satisfy existing or foreseen demand with a smaller amount of water resources. Demand management initiatives include structural (infrastructure improvement) or non-structural measures (information campaigns, pricing) applied to specific sectors and carried out either by the water utility or the end-users [1]. In order for a water utility to identify the optimal mix of demand management and supply enhancement a coherent framework for comparison of alternative options is required.

The procedure to assess the margins for the water demand management that contributes to the financial sustainability of the water supply system involves the following steps:

Estimation of the projected water demand on the basis of the observed trends in tourism and population development

Paros is a small island with an area of 196 km^2 in the middle of the Cycladic complex and one of the most popular tourist destinations in Greece. The annual water demand in Paros for 2001 is estimated at 1.8 mil m^3 assuming an average consumption of 180 lt/capita/d and includes the demand for permanent population, visitors and tourists as well as losses in the water supply system. The daily consumption rate represents an acceptable level of service provision to the consumers for regions with similar climatic conditions. Serious water quotas are imposed as a common practice in an effort to match the actual consumption to the availability of water supply. Population increase has been assumed at 1.5% annually since the main economic activities in the island present high development rates. Tourism is expected to grow at 3% annually for the next decade and 1% thereafter [3, 4].

Development of the Reference scenario

The reference scenario involves only supply enhancement options and provides an indication of the water supply costs for facing the water demand in the island. Groundwater boreholes, surface storage reservoir, seawater desalination and water transport are the main available supply development options.

Development of alternative scenarios including demand and supply management

The optimisation model is used with a combination of supply and demand management measures in order to identify a set of measures that includes different demand management options. The net present value of the supply and demand management costs for each combination is estimated as well as the monthly contribution of each option and the capacity of the supply enhancement options.

Comparison of reference and demand management scenarios

At the final step, the effect of water demand management on the overall water supply costs is assessed. The net present value of the optimum demand and supply management combinations is compared to the reference scenario. The obtained reduction in the overall water supply costs is used as an indicator of the potential of demand management to replace the supply enhancement options.

4 Results and discussion

Figure 1 presents the monthly profile of the water demand and supply in Paros for 2001 and the projected water demand for 2010. Severe water quotas are imposed as a common practice in an effort to match the actual consumption to the availability of water supply.

Reference Scenario

In the reference scenario, the water utility considers only supply enhancement options for meeting the projected demand using the least cost capacity expansion options. Figure 2 presents the optimal capacity expansion option for Paros for 2010. The identified solution involves the use of all existing groundwater boreholes and the construction of a surface reservoir with storage capacity of 250,000 m^3, and a desalination plant of 5,000 m^3/d. Water transport is applied during the peak water demand period to cover the remaining water demand. The net present value for the reference scenario is estimated at 21.6 mil. € for a period of 20 years and a discount rate of 6%.

Desalination is used up to its maximum capacity in the period from May to September. Water transport takes place during July and August when available resources from all other options are not adequate to meet the demand. Monthly demands in May and June could also be met through conventional resources; however it is preferable to use the desalination plant and keep the stored water for the peak demand period in July and August.

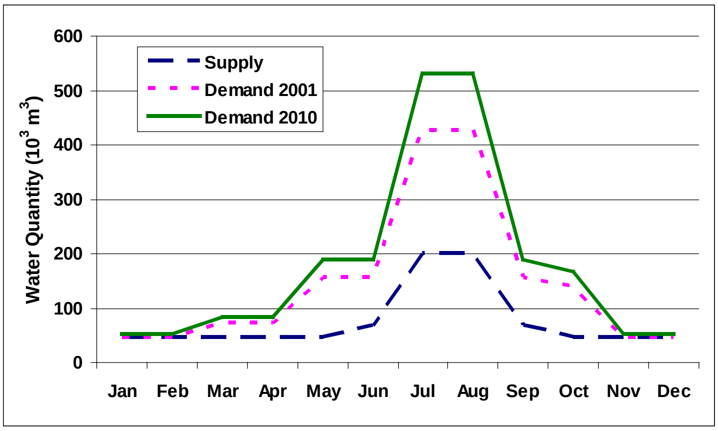

Figure 1. Water demand and supply analysis in Paros for 2001

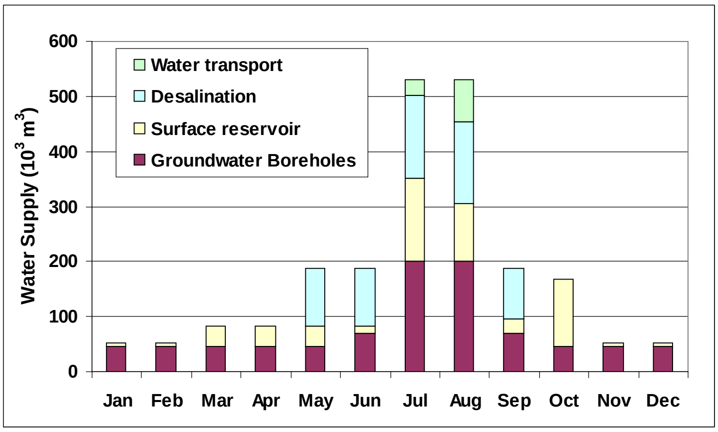

Figure 2. Reference Scenario for 2010

Alternative Scenarios

For the evaluation of demand management actions on the structure of the water supply system alternative water demand management options have been modelled. The introduction of demand management affects the volume of transported water and the capacity of the desalination plant, while borehole capacity remains stable since the level of water savings is low. Table 1 presents the optimum desalination plant capacity identified for each demand management option. For demand management cost up to 1.5 €/m^3, the optimum capacity of the desalination plant is reduced as the level of water savings increases. The optimum storage capacity of the reservoir is reduced when the demand side measures achieve water savings that exceed 50% of the water demand.

Table 2 presents the net present value of the overall water supply costs as function of the demand management cost and the maximum achievable water savings. The maximum monthly contribution of water savings has been defined through the constraints of the optimisation model. Overall water supply costs represent the optimum water management combination and include the costs of both supply and demand management. Results indicate that water demand management reduces the overall water supply costs when the cost of the measures is lower than the cost of the most expensive supply side options. The overall cost reduction is due to the reduction of transported water and smaller capacity of the desalination plant. The overall water supply cost is not significantly reduced when the cost of demand management is higher than the cost of desalination (above 2 €/m^3).

Table 1. Desalination plant capacity (m^3/d) for different demand management options

DSM Cost (€/m^3)	Desalination Plant Capacity (m^3/d)		
	10%	20%	30%
0.05	4733	2789	1788
0.15	4028	2831	1977
0.50	3507	2733	1948

1.00	4583	3139	2096
1.50	4308	3849	2241
2.00	4837		

Table 2. NPV of the optimum water management scheme

DSM Cost (€/m^3)	**NPV of water supply costs**		
	10%	**20%**	**30%**
0.05	18.5	15.6	12.7
0.15	18.8	16.0	13.6
0.50	19.8	17.3	15.3
1.00	20.4	19.1	18.0
1.50	21.2	20.4	20.5
2.00	21.5	-	-

The contribution of the demand management measures is estimated on a monthly basis. Figure 3 presents the optimum water management structure including demand side measures with a cost of 0.5 €/m^3 and maximum water savings at 20%. Water saving measures are more intense in the period May – September, while for the rest of the year the low-cost water supply options are preferred. In July and August water transport is still required because the capacity of supply options is not adequate to face the demand even if the maximum water savings are obtained. When the cost of demand management is higher (2 €/m^3), the optimum water savings does not exceed 10% of the water demand (for the period from June to September) while for the rest of the year it is preferred to increase the exploitation of available resources.

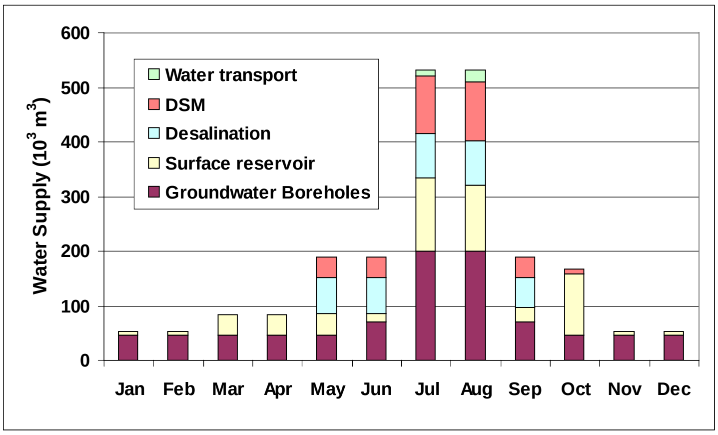

Figure 3. Optimum combination of supply and demand management measures for 2010

The structure of the water supply system presented in Figure 3 is similar for the rest of the scenarios and indicates that demand management measures should target the peak summer period because the cost reduction obtained is higher. Taking into account that tourists contribute the majority of the water demand in summer, it is preferable that demand management measures should target the hotel sector. In this regard, it is preferable for the water utility to promote and finance measures for the improvement of water use efficiency in the hotel sector than to expand the water supply infrastructure beyond the level presented in Figure 3. Potential actions may refer to the subsidization of low-water using appliances, such as taps, toilet flushers, and other hotel equipment, and intensive awareness campaigns during the summer period. In a more general case, the water utility should proceed to the repair of the public water supply system, in an effort to reduce conveyance losses which account for almost 30% of the demand.

Figure 4 presents the reduction of the overall water supply cost as function of the DSM cost and maximum water savings. The overall water supply cost reduction is obtained as the low cost demand management replaces water transport and desalination, which are the most expensive supply enhancement options. The overall water supply cost is reduced as the obtained water savings increase. Demand management measures with average costs equal or higher to that of desalination provide a very small reduction of the overall water supply cost. In this case, it is preferred to face the majority of the demand with supply enhancement options instead of demand management.

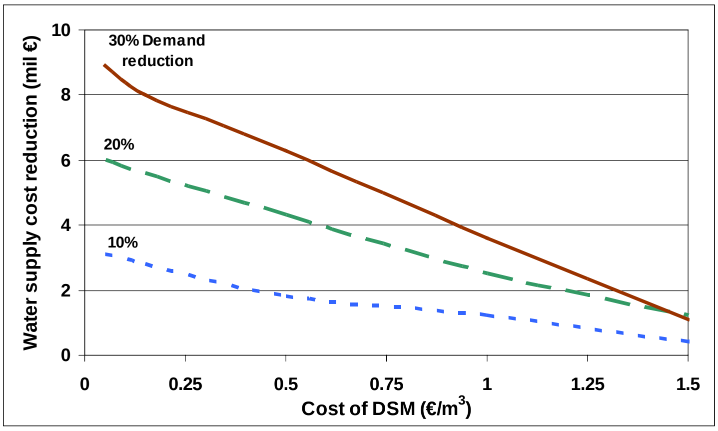

Figure 4. Reduction of water supply cost

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