Water Supply Modeling towards Sustainable Environmental Management in small islands: the case of Paros, Greece

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Abstract

The present approach has a two-fold emphasis. On one hand water supply options are modeled and the optimal combination is presented through the identification of the least cost water supply scheme. On the other hand the results may be used towards the delineation of sustainable environmental policy options, particularly in the vulnerable system of small islands. Hence an optimization model has been developed that minimizes the Net Present Value (NPV) of water supply projected costs for the period 2002 – 2030 for Paros Island, Greece. The non-linear generalized reduced gradient method is used taking the capacity of water supply options as decision variable. The model incorporates the operation of groundwater wells and boreholes, surface storage reservoirs, conventional and wind-powered desalination and water hauling by ships. Finally, it estimates the monthly water production as well as the water supply costs. The identified solution involves the combined use of all water supply options and may provide the optimal contribution of each one of the supply sources, on a monthly time step. The results indicate that conventional water supply topped by versatile desalination schemes used for the particularly demanding water consumption peaks may be the focal area of responses for the island of Paros, and by extension for other areas around the world facing similar problems.

1 Introduction

The economic activities in small islands in Greece rely mostly on summer tourism, which gradually replaced traditional practices such as agriculture or fishing. Therefore, water demand presents a high seasonal variability creating significant pressures on existing water resources [4]. Serious water shortage problems occur for a period not exceeding one or two months. The very short duration of the peak demand has, in most cases, prohibited the development of solutions that require significant investment costs such as desalination plants and surface storage reservoirs. The predominant water management practices are restricted to a very limited set of water supply options that include, in most cases, overexploitation of groundwater resources and transport from the mainland. Conventional or renewable energy powered desalination is applied in cases where there is a lack of local water resources throughout the year [1, 11]. On the other hand, water supply quotas for long periods, high water prices, consumer demands for improved services, and an increased rate of regional development do not foresee any further reduction of the water consumption patterns. Consequently, water supply efforts in Greek islands have to anticipate an increasing water demand that should be met at minimal costs without setting further pressures to the already stressed water resources. Under such conditions, desalination, compared to conventional water supply related interventions, may take an advantageous position in terms of economic costs and environmental impacts [11].

Recent trends in water management for small islands recognise the long-term environmental impacts of traditional / existing water management practices [11, 12]. Environmental impacts apart from those associated with wastewater, haphazard and urban tourist development, are mainly concentrated on seawater intrusion in coastal aquifers. Such an intrusion is mainly attributed to the overexploitation of groundwater resources and the increasing water deficit due to the low natural recharge rate of such resources. The associated impacts produce a chain reaction in the whole fragile ecosystemic integrity [1-4]. As a result, the main socio-economic consequence is the highly inefficient operation of the water supply system (salt deposits, high operation cost), due to the high cost of water transport, although the consumer prices are among the highest in the country. In this regard, water supply options are approached in the current effort towards the development of an optimisation model for the identification of the least cost water sources able to cover the anticipated water demand in a long-term planning horizon.

Available solutions such as desalination and surface storage reservoirs, are characterised by high investment costs while other options such as water transport present very high operation costs and low initial investments (since in most cases rental ships are used). The optimal water supply scheme could be identified through the minimisation of the overall water supply costs for the entire planning period taking into account the annual water demand profile and the available water resources.

Optimisation models have been extensively used to solve complex water supply problems in combination with simulation models for the detailed assessment of environmental or technical constraints [5 - 10]. However, their use for the analysis of existing practices and the design of integrated water supply management approaches in small arid islands has been rather limited. In the present work an optimization model for the island of Paros in Greece is developed and used for the identification of the optimal water supply enhancement to the existing infrastructure. The objective is to identify the margins for the development of non-conventional water supply options, such as desalination and water hauling. Available simulation models for all potential water supply options are integrated into an optimisation model that minimises the total water supply cost. The potential contribution of each option is bounded by upper and lower limits, which are defined on the basis of technical and environmental constraints.

2 Water management context in Paros

Cyclades is a complex of 39 islands in the south Aegean Sea in Greece. The population is 112,000 and tourists' arrivals reach 400,000 annually. In the most developed islands the population during the summer months increases as much as 5 times. Paros is a small island with an area of 196 km^2 in the middle of the complex and one of the most popular tourist destinations in Greece. Figure 1 presents the monthly population distribution in the island.

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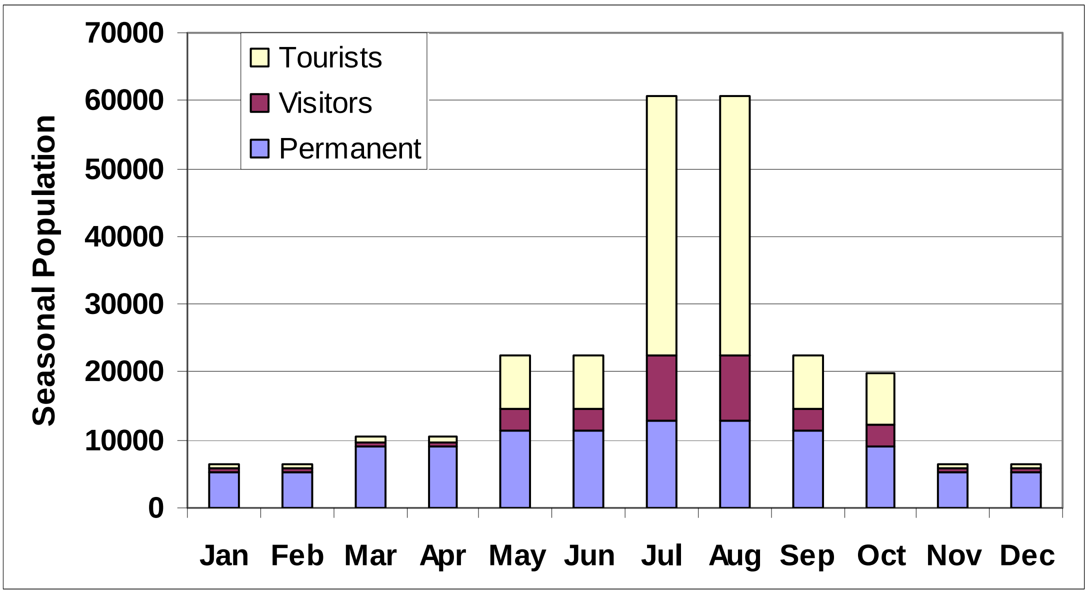

Figure 1. Monthly population distribution in Paros (2001)

Annual water demand for the year 2001 is estimated at 1.8 million m^3, assuming an average daily consumption of 180 lt/capita, including the demand for permanent population, visitors and tourists, and losses in the water supply system. The daily consumption rate represents an acceptable level of service provision to consumers of 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. Figure 2 presents the monthly profile of the water demand and supply in Paros. Aquifers, which provide about 95% of the consumed water, are highly overexploited during the summer in an effort to follow the demand profile. Seasonal storage of rainwater in private cisterns contributes about 5% of the water consumption.

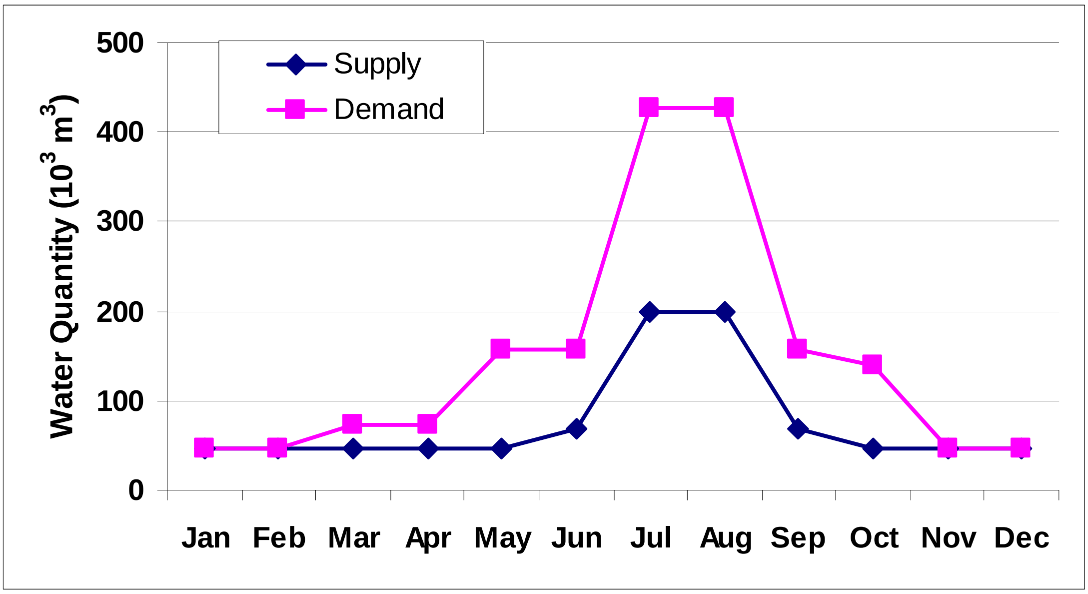

Figure 2. Water demand and supply analysis in Paros (2001)

The permanent population in the island has increased over 50% in the last two decades as a result of the extensive immigration following the tourism industry development. Such a trend is expected to continue during the next decades at a rate of 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 period up to 2010 and 1% for the next two decades [11]. Assuming constant daily water consumption rates, water demand in the island is estimated at 2.5 million m^3 in 2020 and 2.9 million m^3 in 2030.

Possible supply augmentation projects in the island include expansion of the groundwater exploitation, development of surface water storage reservoirs and installation of conventional or wind-powered desalination plants. The morphology of Paros does allow for the development of storage reservoirs with adequate capacity to meet the peak demand although the average water supply costs are relatively low. Desalination plants provide a reliable and highly flexible water supply pattern that could efficiently follow demand variations. The high investment cost, however, limits the maximum penetration at levels well below the peak water demand. Water transport requires very low investment costs and could be employed to cover any water shortage; however, the transportation cost for Cyclades is very high. Financial goals should be set to minimise the cost of applied solutions and avoid a large pressure on water prices, while clear environmental objectives should be set to protect the fragile water reserves and allow the rehabilitation of the aquifers.

3 Optimisation model

The identification of the most appropriate water supply option should not be based only on the comparison of the average annual costs. It represents an optimization problem that takes into account the water demand profile and the potential contribution of each alternative water supply source. The optimisation model is formulated as a non-linear problem with the objective to minimize the net present value of the water supply cost for the period up to 2030. Figure 3 presents the optimisation algorithm.

The optimisation model was based on the assumption that the water demand is met at all times. Water hauling is the most expensive one due to the high transportation cost that may reach 2.5 €/m^3. Consequently it has been considered that water transport covers the unmet demand when all other options are used up to their maximum potential.

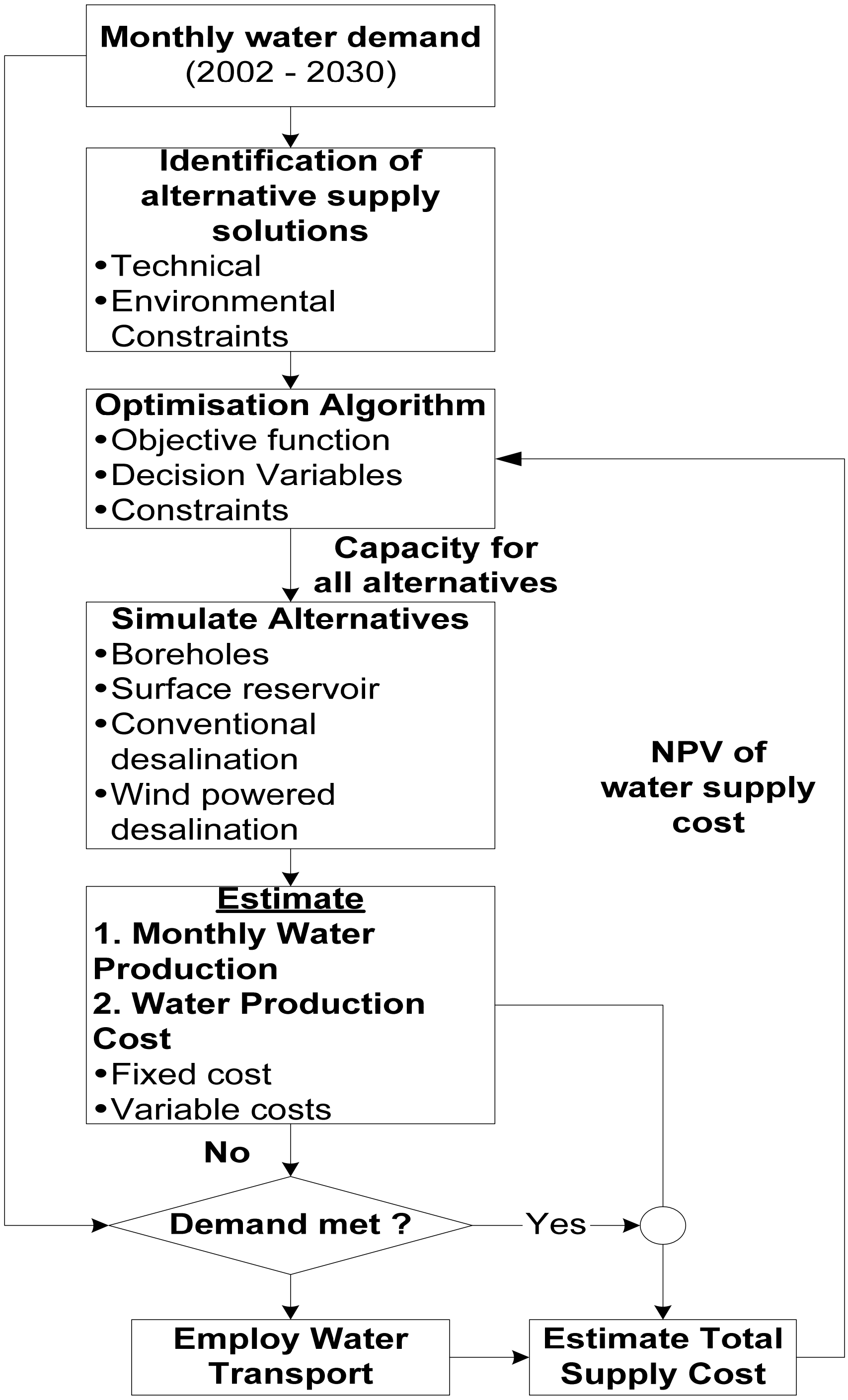

Figure 3. Problem Formulation and Optimisation algorithm

3.1 Objective Function

The objective function is the minimisation of 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 2030 is analysed.

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

C_k = Total water supply cost for year k (k=1 – 28 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. Eq. 2 estimates the total annual water supply cost.

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

$AC_{j,i,k}$ = 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: (1) groundwater boreholes, (2) surface storage reservoir, (3) conventional desalination (4) wind-powered desalination and (5) water hauling 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). In order to estimate $Q_{j,i,k}$ it has been assumed that alternative options are employed successively, according to ascending water supply costs until the monthly water demand is met. In this case, the simulation models are used to estimate the maximum monthly water production from each source.

Groundwater boreholes

The monthly water production from groundwater boreholes has been estimated according to the current boreholes 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 of boreholes capacity will not create irreversible problems to groundwater resources. Consequently, a capacity increase of 1% annually is assumed for the next decade and then maintained at this level for the rest of the analysed period. The monthly water production from groundwater boreholes is modelled by Eq. 3:

$$QM_{1,m} = G \cdot b_i \cdot B \qquad (3)$$

$QM_{1,m}$ = Maximum water production from boreholes for period m (m =1- 336 months)

G = Fraction of the total boreholes capacity used

b_i = Fraction of the available boreholes capacity that is in operation in month i (1=1-12)

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 for groundwater boreholes, including fixed and variable costs are estimated at 0.28 €/m^3.

Surface storage reservoir

The simplified water balance for a surface water storage reservoir is modelled by the following equation:

$$V_m = V_{m-1} + I_m - E_m - Q_m \qquad (0 \le V_{mi} \le V_{\max}) \qquad (4)$$

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 the inflows exceed the storage capacity of the reservoir, excess water is rejected. Thus, maximum monthly water availability is determined by the storage capacity of the reservoir. Evaporation losses are calculated using the average values in existing cases in the islands [4].

Water abstraction is estimated as a fraction of the monthly water demand and cannot exceed the monthly availability of water in the reservoir (Eq 5).

$$QM_{2,m} = \min(V_{m-1}, a_i \cdot D_{2,m}) \quad (5)$$

$QM_{2,m}$ = 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 6 and includes construction costs, land acquisition, network construction and water cleaning equipment. Eq. 6 has been derived from exponential interpolation of available cost data from 94 operating storage reservoirs in Greece [13]. Project lifetime is assumed to be 30 years.

$$CC_2 = 1090.8 \cdot (V_{\max})^{0.61} \quad (6)$$

CC_2 = Investment cost for a surface storage reservoir

The operational cost (OM_2) includes maintenance and labour costs and has been estimated at 0.16 €/m^3.

Conventional desalination

The monthly water production for a grid powered reverse osmosis desalination plant is determined using Eq. 7:

$$QM_{3,m} = Des \cdot t \quad (7)$$

$QM_{3,m}$ = 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 2,500 m^3.

The most important components of the investment cost for conventional reverse osmosis plants include the membranes and electromechanical equipment costs. The capital cost for the wind powered desalination plant is modelled with Eq. 8, derived through exponential interpolation of cost data collected from operating desalination plants in Greek islands. The annualised investment cost has been estimated assuming the plant lifetime at 15 years. It should be noted that plants are replaced at the end of their lifetime.

$$CC_3 = 2270 \cdot (Des)^{0.875} \quad (8)$$

CC_3 = Investment cost for a reverse osmosis plant

The operation and maintenance costs (OM_{des}) are estimated on the basis of the parameters presented in Table 1 and include energy, chemicals, membrane replacement, and labour costs [14]. 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 reverse osmosis plants with capacity in the range of 500 – 10,000 m^3/day.

Table 1. Operational parameters and costs for reverse osmosis desalination plant

Conversion Factor	38%
Specific energy consumption (kWh/m^3)	5.00
Chemicals (kg/m^3 produced water)	0.278
Membrane replacement (parts/m^3 feed water)	0.005
Chemicals cost (€/kg)	0.15
Membrane replacement cost (€/part)	6.16
Electricity cost (€/kWh)	0.09
Labour (€/m^3)	0.15
Annual membrane replacement rate (%)	12
Other (% of the operational cost)	10

Figure 4 presents the average water production cost for conventional desalination plants as function of the capacity of the plant and the annual operation time.

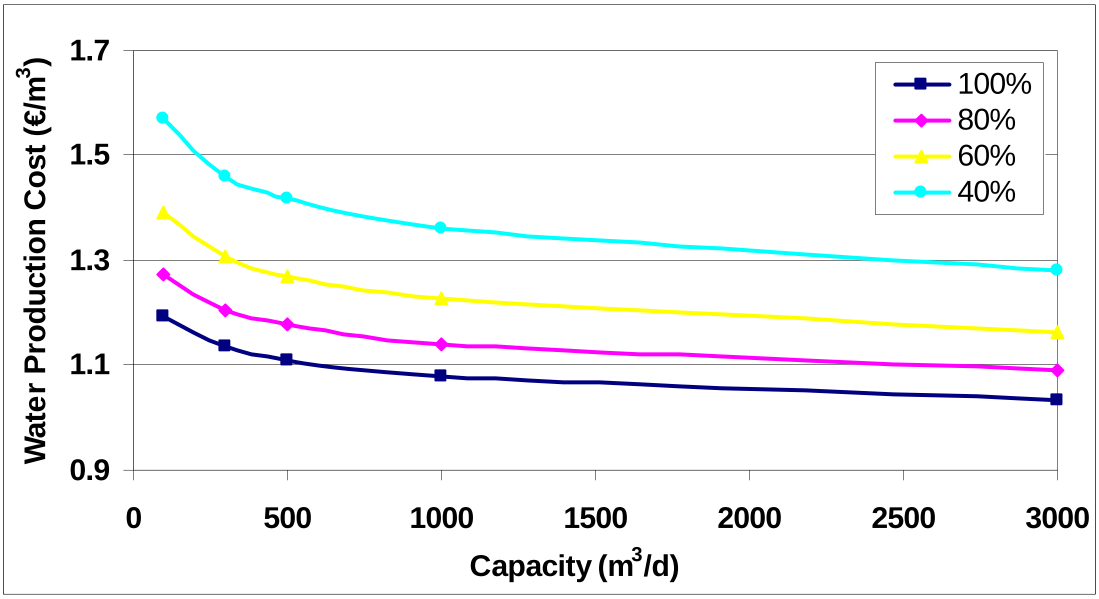

Figure 4. Water production cost for conventional desalination plants

Wind powered desalination

The monthly water production of a wind powered desalination plant is estimated according to Eq. 9.

$$QM_{4,m} = WDes \cdot t \qquad (9)$$

$QM_{3,m}$ = Maximum water production from the wind powered desalination for period m

WDes = Daily capacity of the wind - desalination plant

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

The produced energy from a wind turbine depends on the power curve of the wind-turbine and the instant wind speed. The probability of occurrence of a specific wind speed is usually modelled by the K-Weibull distribution and depends on the mean annual wind speed at the site. The instantaneous power output of a wind turbine is a function of the wind speed at the rotor height and is given by the power curve P(U). The power curve of a SEEWIND 20/110 wind turbine with nominal capacity of 110 kW has been used for the estimation of the annual energy production of the wind turbine using Eq. 10:

$$E_{WT} = 8760 \cdot \int_{0}^{Ucutout} p(U) \cdot P(U) dU \tag{10}$$

E_{WT} = Annual energy production of the wind turbine

U_{CutOut} = Maximum operating wind speed

$P(U)$ = Power output at wind speed U

Assuming that the wind turbines can provide the desalination plant with power up to P_{des}, the maximum annual wind energy that the desalination plant can absorb is estimated by Eq. 11. The power produced during high wind speeds that cannot be used in the desalination plant is rejected.

$$E_{WT \to DES} = 8760 \cdot N_{WT} \cdot \left[\int_{0}^{U_{Pdes}} P(U) p(U) dU + \int_{U_{Pdes}\,0}^{U_{cutout}} P_{Pdes}\, p(U) dU \right] \tag{11}$$

$E_{WT \to DES}$ = Wind energy absorbed by the desalination plant

N_{WT} = Number of wind turbines

U_{Pdes} = Wind speed which corresponds to the rated power of the desalination plant at the power curve of the wind-turbine

Electricity from the grid provides the energy required for the operation of the plant during low wind speed. The annual energy flows from the grid is estimated by Eq. 12.

$$E_{Grid \to DES} = E_{DES} - E_{WT \to DES} \tag{12}$$

The capital cost for the wind powered desalination (CC_4) plant is estimated using equation 13:

$$CC_4 = 2270 \cdot (Des)^{0,875} + CC_{WT} \tag{13}$$

Des = Capacity of the desalination plant

CC_{WT} = Investment and installation costs for the wind turbines

Investment and installation cost for the wind turbines include purchase and installation costs, road and power network construction. The cost of the wind turbines has been estimated assuming a price of 1000 €/kW. Operational costs have been estimated as function of the number of wind turbines assuming an annual cost of 5800 €/wind turbine.

Energy costs are estimated on the basis of the consumption of grid electricity, calculated from Eq. 12. Other components of the operational cost for the desalination unit are estimated on the basis of the parameters in Table 1.

3.2 Decision variables and constraints

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

- 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 ($0 < Des < 2500$)
- Daily capacity of the wind - desalination plant ($0 < WDes < 2500$)

4 Results and discussion

Figure 5 presents the average water production cost for the potential solutions that have been discussed for Paros. The capacity of the reverse osmosis plants is 1000 m^3/d, wind speed at the site is assumed at 8 m/s, and storage reservoir capacity is set at 250,000 m^3.

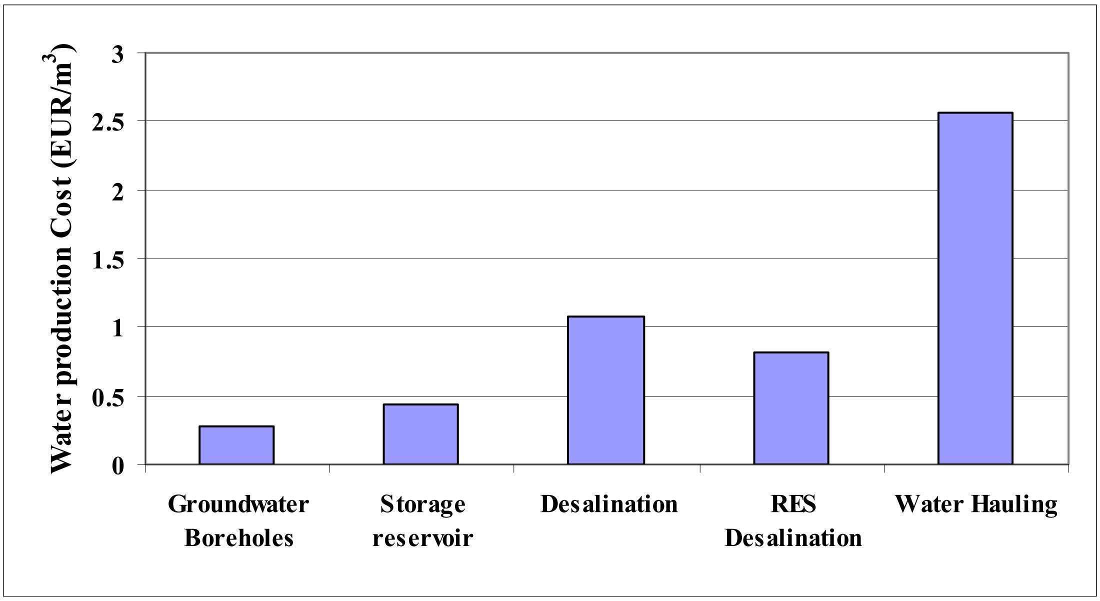

Figure 5. Comparison of the water production costs for alternative water supply options

Figure 6 presents the water supply options for 2010 according to the optimum solution identified. Groundwater is used at 100% of the existing capacity due to the very low cost compared to all other options. The storage reservoir capacity has been identified at 250,000 m^3 which is the maximum capacity determined by the problem constraints. The contribution of the storage reservoir in May, June and July has been determined during the optimisation at 26%, 11% and 51% of the demand not covered by groundwater. In this way, the reservoir holds enough water for use in August when the peak demand occurs. Alternatively if the usage of the reservoir in this period is more extensive then in August most of the demand will be cover by water transport and the total costs will be higher.

The capacity of the conventional desalination plant has been determined at 1500 m^3/d and the capacity of the wind powered plant at 2,500 m^3/d, taking into account that operational costs of the wind powered plant are much lower that the costs of the conventional one. Desalination plants are used to their maximum capacity from May to September. The capacity of the conventional desalination plant is not further increased since fixed costs exceed the cost of water hauling that is employed for July and August.

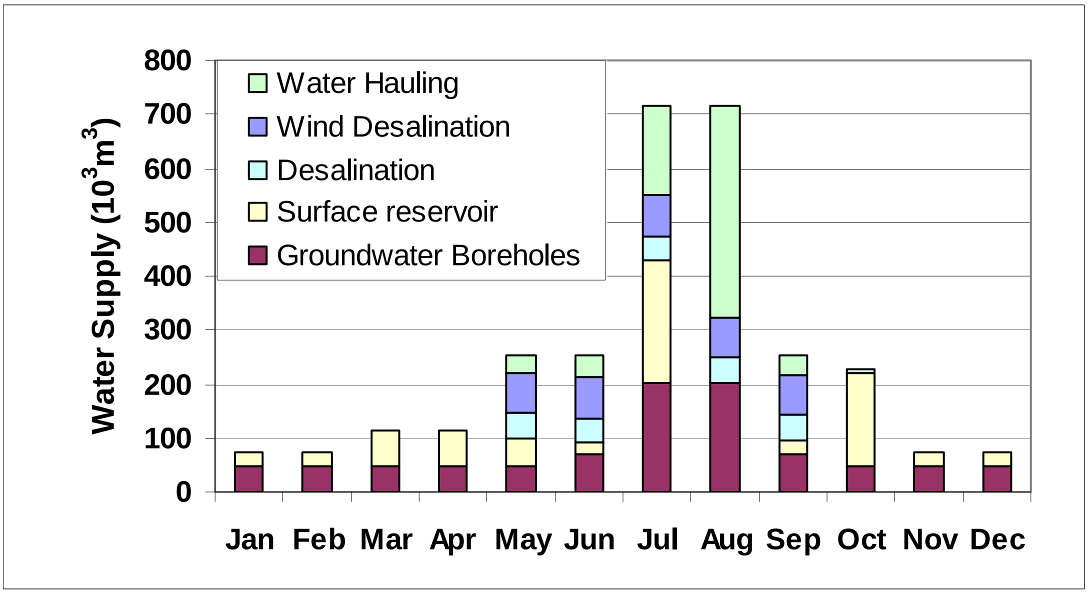

Figure 6. Contribution of alternative options in 2010

5 Conclusions

The management of the limited and fragile water resources in small islands requires the adoption of innovative practices and solutions both on the supply and demand of the water systems. In a fast changing era, any present or future oriented water resources development and management scheme should be also able to cope with the larger aims of social and economic dimensions. At the same time, supply augmentation and demand reduction measures are both influencing the rate and the extent of change in the environment. Underlining all such considerations is the centrality of sustainability and equitable sharing of water resources. Given such considerations, the approach suggested in the present work seems to address more completely the challenges associated with water supply options in an island environment.

The presented case study may introduce a coherent approach in modelling alternative technical interventions and identifying the economically optimum water supply scheme in an effort to match demand and supply. All in all, it may be demarcated that groundwater should be used as the basic supply. As demand increases, surface reservoirs should be used followed by wind-powered desalination. Then conventional desalination should be incorporated, and last, water hauling by ships should meet the peak demand. In regions with a demand profile similar to that of Paros, desalination plants are operated only during the summer increasing the average production cost. However, desalination holds a central role towards the development of a water supply system able to face the anticipated water demand at minimal cost without setting further pressure on natural water resources.

Such an identification of the least cost water schemes for small islands is also of significant importance towards financial sustainability of the water supply scheme. Finally, it is believed that the overall approach may provide the tools and the methods to assist in the implementation of a balanced demand and supply towards environmental sustainability.

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