OPERATIONS RESEARCH METHODS IN WATER SYSTEMS OPTIMISATION.

Emilia Kondili

Optimisation of Production Systems Lab., Mech. Engineering Dept., TEI of Piraeus,

250 P. Ralli and Thivon, 122 44 Aegaleo, e-mail: ekondili@teipir.gr

John K. Kaldellis

Soft Energy Applications and Environmental Protection Lab.,

TEI of Piraeus, 250 P. Ralli and Thivon, 122 44 Aegaleo, e-mail: jkald@teipir.gr

ABSTRACT

Water is a valuable natural resource with very high importance, especially in areas with water shortage. During the last years the limitations in water availability in various areas make the solution of water problems extremely urgent and important. In Greece, temporary or continuous water shortage appears in various areas, especially in the islands, mainly due to their geomorphology and the population increase during summer.

The objective and the aims of the present work are:

- to make a short review of the operations research methods that are used to solve water resources management problems,
- to describe the project that has recently been implemented in the framework of ARCHIMEDES programme in TEI of Piraeus for the water systems optimisation in areas with limited water resources, and
- to analyse the basic ideas and proposed solutions in the aforementioned project.

More specifically, the basic idea of the project is the development and implementation of an optimisation model that selects the quantities of water to be supplied from various sources and the quantities of water to be allocated to various users, in order to optimise the total water value, taking into account priorities in the demand and use of the resource, as well as sustainability considerations.

Keywords: Operations research methods and tools, water resources management, water systems optimization, systems modeling.

Μέθοδοι Επιχειρησιακής Έρευνας στην Αριστοποίηση Συστημάτων Νερού σε Νησιωτικές Περιοχές

ΠΕΡΙΛΗΨΗ

Το νερό είναι πολύτιμος φυσικός πόρος, ανέκαθεν μέγιστης αξίας σε περιοχές με περιορισμένους υδάτινους πόρος. Τα τελευταία χρόνια η σημασία του καθίσταται ολοένα μεγαλύτερη λόγω συνεχώς παρατηρούμενης έλλειψης. Στην Ελλάδα παροδική ή μόνιμη έλλειψη νερού υπάρχει σε πολλές περιοχές και ιδιαίτερα στα νησιά, οφειλόμενη αφενός μεν στη γεωμορφολογία αφετέρου δε στην ιδιαίτερα μεγάλη αύξηση του πληθυσμού κατά τους καλοκαιρινούς μήνες.

Σε πολλές περιπτώσεις το μείζον πρόβλημα δεν είναι αυτή καθαυτή η έλλειψη του νερού αλλά η μη ορθολογική αξιοποίησή του. Σε περιπτώσεις που η συνολική διαθέ-

σιμη ποσότητα νερού δεν αρκεί να καλύψει τη ζήτηση, η αποτελεσματικότητα της κατανομής των υδάτινων πόρων, δηλαδή ποιες ποσότητες θα κατανεμηθούν σε κάθε ομάδα χρηστών σε κάθε χρονική περίοδο, είναι ένα σύνθετο πρόβλημα που χρήζει συστηματικής αντιμετώπισης.

Στην πραγματικότητα η διαχείριση και η ορθολογική αξιοποίηση των υδάτινων πόρων (water resources management) είναι μία σειρά από ιδιαίτερα ενδιαφέροντα προβλήματα, είτε σε τοπικό επίπεδο ή συνολικά σε μια περιοχή ή και μία χώρα, για μια συγκεκριμένη χρονική περίοδο ή στη γενική τους μορφή, στα οποία βρίσκουν εφαρμογή οι μέθοδοι αριστοποίησης της επιχειρησιακής έρευνας.

Στην παρούσα εργασία αναφέρονται οι κυριότερες εφαρμογές των μεθόδων και προσεγγίσεων Επιχειρησιακής Έρευνας σε προβλήματα των υδάτινων πόρων. Επίσης παρουσιάζονται τα κυριότερα συμπεράσματα και αποτελέσματα ερευνητικού έργου στα πλαίσια του Προγράμματος ΑΡΧΙΜΗΔΗΣ που ολοκληρώθηκε πρόσφατα και αναφέρεται στην Αριστοποίηση Συστημάτων Νερού σε νησιωτικές περιοχές με περιορισμένους υδάτινους πόρους.

ΛΕΞΕΙΣ – ΚΛΕΙΔΙΑ: Διαχείριση υδάτινων πόρων, Αριστοποίηση Συστημάτων Νερού, Μοντελοποίηση Συστημάτων νερού.

1. INTRODUCTION

Water is a constrained natural resource and in many areas of the planet water shortage is considered to be possibly the most critical issue to be resolved. Water supply chain management and optimisation are evolving as the most difficult and urgent problems, since the water demand and availability vary significantly with time.

Various approaches have been proposed for the solution of partial or integrated water resources management problems. However, an acute and difficult to resolve issue is the water allocation, i.e. the distribution of the available water resources in a consistent and accepted method and/or tool, depending on the urgent and crucial role of the water in each of the suggested uses.

The aim of the present work is to investigate the usefulness of the operational research tools in the solution of water resource management problems. Furthermore, the work presents a research project being currently in its last stages that has been implemented in TEI of Piraeus concerning the exploitation of optimisation methods for the optimisation of water resources in areas with water shortage.

The proposed system is based on a generic optimisation model that takes into consideration the whole set of problem features and parameters. Cases where water demand exceeds water availability can be taken into account by assigning priorities to the users. The underlying idea is that the optimal allocation of the available water is an issue of crucial importance in the overall water resources management problem and should be determined according to the needs and the expected use of water.

During the last decades several methodologies have been developed in the design and operation of water systems, in the field of engineering. In spite of the interest that has been shown in the water resource optimisation problem from various researchers and practitioners, there is always a scope for applied research in the development of tools that match local needs and take into account the specific characteristics of the area under consideration.

2. OPERATIONAL RESEARCH METHODS IN WATER RESOURCES MANAGEMENT

Operational research methods, especially optimization methods for constrained resources have been widely applied in water resources problems [1]. In fact the OR methods provide valuable systems analysis tools that fit very well to the natural resources problems in general, trying to model in a rational way their behaviour and the associated decision making.

The optimized planning of a water-resources system is usually carried out through constructing a mathematical model of the system, and is solved by systems analysis or methods of mathematical programming. Such a mathematical model is frequently characterized through a number of equality and inequality constraints, expressing physical laws and/or limitations in some system components.

There are many types of water resources problem that have been approached with optimisation methods [2-4], such as:

- Water allocation between competing users in a certain geographical region.
- Water resources management and water supply optimisation techniques in agriculture (irrigation).
- Analysis and planning of multipurpose water resources systems with integrated mathematical models.
- The problem of determining the optimal operating policy for a system of reservoirs.
- Evaluation of alternative scenarios for water pricing.
- Optimization of water distribution plans.

In fact, many works concerning water management problems have been published in relevant to OR journals. The solution techniques employed are Linear Programming, Mixed Integer Linear Programming, Dynamic Programming, Multiobjective Optimisation.

Furthermore, the use of OR tools may form the basis for the development of water resources Decision Support Systems [5] that facilitate the allocation of water resources in users, depending on the availability and priorities in its use.

3. WATER RESOURCES MANAGEMENT IN THE AEGEAN ISLANDS

Cyclades and Dodecanese are island complexes belonging in the South Aegean Prefecture and located in the Southeastern part of Greece, a region which is characterized by special architecture and interesting cultural tradition, pleasant climate, especially during summer and attracts many tourists. However, the temporal increase of population in combination with the local activities, mainly agricultural, commercial and rarely industrial, the low precipitation rates, the geomorphology of area and over-exploitation of groundwater resources, have led to extensive water shortage problems.

The water availability in the Aegean islands varies with time and definitely plays a critical role in the regional development and the living conditions of these islands. The local water resources are relatively limited, especially in the small islands. In many cases, where the water scarcity is extensive, the needs are partially or totally covered through ship transport, which is a temporary solution, because it does not form any infrastructure for the long-term solution of the problem.

Figure 1: Map of Cyclades and Dodecanesse islands

Cyclades in particular is an island complex including many, arid in their majority, islands. The medium-large size islands, such as Syros, Naxos, Andros, Myconos, with high development rates, have partially solved their water shortage problem with infrastructure projects, such as desalination plants, water dams and ground water reservoirs. However, the smaller ones are forced to adopt short term solutions i.e. water transport by ships and the storage of it in water reservoirs. It must be pointed out that during the last decade a water volume of 1,620,000m^3 has been transported to Cyclades Islands with an overall cost 12,524,000 € [6].

Accordingly, in Dodecanese Islands only the large-size ones, like Rhodes and Kos have their own water resources, while the majority of the rest acquire the demanded quantity through transport from the larger ones, even though during the last years some desalination plants have been constructed. The corresponding imported quantity in Dodecanese islands for the period 1997-2005 has been 4,508,000 m^3 with an overall cost 18,739,000 € [6].

In some of the Aegean islands, the water supply problem is solved either partially or completely with the operation of local desalination plants, based on the Reverse Osmosis technology. In general, the cost of water from desalination plants is much smaller than the corresponding cost of transported water. In any case, in the proposed model the water cost from each different supply source is taken into account.

4. A NOVEL METHOD FOR OPTIMISATION OF WATER SYSTEMS

A research and development project has recently been carried out in the Mechanical Engineering Department of TEI of Piraeus within the framework of ARCHIMEDES programme in the period of 2005-2008, concerning the optimisation of water systems in areas with limited water resources. The objectives of the project are [7]:

- To study different technical and economic parameters of water supply methods and (water) uses.

- To develop and implement an appropriate mathematical model for the optimal design and operation of the water systems.
- To define the evaluation criteria and the constraints in water systems' operation.
- To integrate the optimization results and suggest optimal solutions for the design and operation of water systems.

The area that has been selected as the focus of the project is the Aegean islands, where the water shortage is a real and urgent problem.

The project has been structured in a number of workpackages, each one with clear objectives and expected results. The project included the following activities:

- Review of the current status in the water supply and demand in Aegean islands.
- Comparative evaluation of different water supply methods in terms of cost, availability and sustainability.
- Development of an optimization model for the water system that takes into account different supply methods and water demand patterns.
- Investigation of the potential for the combined production of clean water and energy exploiting renewable energy sources [8].
- Implementation of the optimisation model in various representative islands.
- Synthesis of project results and recommendations for the optimal operation of water systems in selected representative islands.

In its current status, the project investigates the possibility of a Decision Support System development, based on the above method, for the optimal exploitation of water resources in the aforementioned islands. The use of this system will be to facilitate the water allocation between competing users and to evaluate in a concise manner alternative scenario concerning water supply and demand.

Furthermore, the research work in its next stages will investigate the applicability of the ideas in other resources (e.g. energy) or in other geographical areas with different characteristics.

5. THE PROPOSED MATHEMATICAL MODEL

<u>Basic Characteristics and Structure of the Proposed Model</u>

As mentioned above, the proposed Decision Support System relies on an optimisation model that identifies the optimal solution in the operation of the water system, taking into account:

- Various supply sources, each one with an associated possibly time varying water cost and a certain and possibly time varying capacity.
- Various users, each one associated with a time varying demand and an also time varying benefit created from the use of water (expressed as a monetary value per cubic meter of water).

The objective of the model is to determine the appropriate water quantities allocated to each user and the input flows from each supply source, keeping in mind that the total water availability may be less than the total demand. Therefore, there may be time periods that not all the demands will be satisfied. The allocation of the available water quantities will be made following the more sustainable principle that the real and most urgent needs must be satisfied first. In parallel, possible inefficiencies of the water system will be identified, such as serious shortages at a certain time periods, inadequate supply from some sources, extremely high cost solutions etc. Figure 2 shows a schematic representation of the system under consideration.

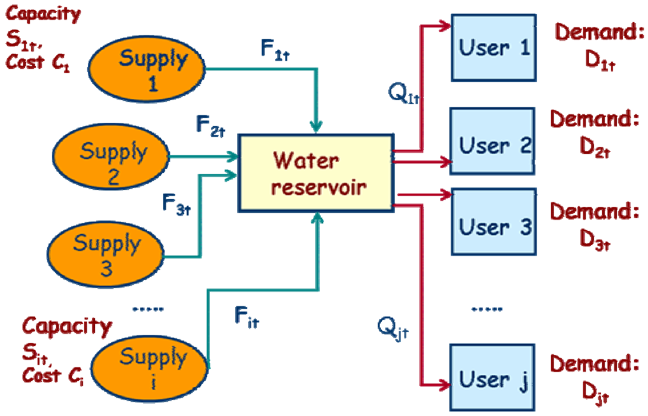

Figure 2: Schematic representation of the water system

The supply sources provide water in a real or virtual storage tank; the storage tank has a specific capacity (upper limit) and a low limit that should never be violated. In case there is no real storage tank, the lower and the upper capacity limits are set equal to zero and the water goes directly from the supply source to the user.

Water Supply

For the islands, the most common water supply sources are the following:

- Desalination units
- Ground Reservoirs
- Dams
- Water transport by ships
- Other own water resources (e.g. wells)

In fact the model can accommodate any type of water supply. The information that is required is the cost, capacity and any existing operational constraints. The supply limits are determined from the capacity of each specific source that possibly varies with time.

The supply costs may simply be considered as linear terms multiplying the corresponding water quantity or may follow more complicated economic functions. For example, the desalted water cost may be calculated as the sum of a fixed term, expressing the depreciation of the unit and a variable cost term or be expressed with a more complicated economic function, taking also into account various parameters of the unit's operation [7]; the same is valid for the ground reservoir and the dam. On the contrary, the water transported by ships has only a rather high variable cost term that is multiplied by the corresponding transported quantity.

Water demand

The most common water users are:

- The agriculture (irrigation).
- The urban use (including permanent and seasonal domestic and commercial use).
- The industry and, possibly, some other secondary uses.
- Other surrounding places that have serious water shortage and need to be supplied by the water supply sources under consideration and can be considered as discrete users with their own demand.

The upper limits of the quantities being delivered to the various users are the corresponding time-varying demands. In case the total water demand exceeds the available quantities, not all the requirements will be satisfied. This will definitely have some impacts to the users (e.g. cancellation or limitation of expansion plans, direct economic losses, decreased agricultural production etc.).

The allocation of the available water to users will be indicated by the optimization, following the priorities that will be set to the model. It should be emphasized that the model will allow the water demands to exceed the total availability, and, therefore, some users demands to be partially satisfied, since the water allocation will be done following certain and predetermined priorities. In fact, this is one of the most interesting parts of the work, sine the priorities that are set follow the value or the expected benefit from the corresponding use of the water and these 'benefits' are the parameters that multiply the quantities allocated to each user in the optimization criterion.

In any case, the discrepancy between the allocated quantity and the demand should be penalised. Actually these penalties are expressed as 'cost terms' in the objective function, caused by the water shortage for a certain user at a time period. The penalties reflect in some way the losses caused by the water shortage and must be time varying, since the consequences of the water shortage are not all the times the same for a user.

System parameters and variables

The variables and the parameters of the system are shown in Tables 1 and 2 respectively. The optimal planning problem will be solved in a predetermined time horizon. The length of the time horizon depends on the specific problem under consideration, the time period of the year and the desired use of the results [7].

Parameter	Magnitude
Index i	Supply source, i.e. dam, ground reservoir, desalination unit, water transport
Index j	User, i.e. irrigation, urban sector, industry, other adjacent places
t	Time step in the horizon under consideration
B_{jt}	Benefit for the use of the water from user j at time interval t (in €/m^3)
D_{jt}	Demand of water from user j at time interval t (m^3)
Q_{jt}^{MIN}	Minimum water flow to user j at time interval t (m^3)
S_{it}	Capacity of the supply source i (m^3) at time interval t
P_{jt}	Penalty for not satisfying the demand of user j at time interval t (€/m^3)
C_{it}	Cost of water from supply source i at time interval t (€/m3)
V_{max}	Maximum volume of water that can be stored in the storage tank (m^3)
V_{min}	Minimum volume of water that should be stored in the storage tank (m^3)

Table 1. Model Parameters

Variable	Magnitude
F_{it}	Flow of water from supply source i at the time interval t (m^3)
Q_{jt}	Water flow allocated to user j at time interval t (m^3)
V_t	Water volume stored in the reservoir at time interval t (m^3)

Table 2. Model Variables

Optimisation Criterion

The optimisation criterion that expresses the efficiency of the water system is the maximisation of the total water value, taking into account all the benefits from the water use, including environmental benefit and costs:

Maximize Total Value of Water = Maximize (Total Benefit – Total Cost)

Total Benefit = $\sum_{t} \sum_{j} B_{jt} * Q_{jt}$,

Total Cost = Supply Cost + Penalties for the discrepancy between demand and real supply to the users.

Hence, the Total Cost term in the objective function is expressed as:

Total Cost = $\sum_{t} \sum_{i} C_{it} * F_{it} + \sum_{t} \sum_{j} p_{jt} * (D_{jt} - Q_{jt})$

Therefore, the optimality criterion that maximises the total benefits and, at the same time, attempts to minimise as much as possible the costs and the differences between the quantities supplied to the users with their real requirements, is expressed as follows:

$$\text{Max } \sum_{t} \sum_{j} B_{jt} * Q_{jt} - \left[\sum_{t} \sum_{i} C_{i} * F_{it} + \sum_{t} \sum_{j} p_{j} * (D_{jt} - Q_{jt}) \right] \quad (1)$$

As shown in the objective function (1), the Benefits from the allocation of a water quantity in user j vary with time. For example, the Benefits for the allocation of water in the urban sector (e.g. tourism) may be much more significant during summer, while the irrigation water will have a larger Benefit in another time interval. Therefore, the values of the Benefits for each user at each time period should accommodate the following issues / concepts:

- The potential results / impacts from the water use, either as revenues or profits from this specific use (e.g. income increase attributed to the water availability from the tourism sector or from the increase in agricultural production).
- A quantification of the regional development and welfare of the local community attributed to the water availability.
- An environmental benefit resulted from the water waste and the resource depletion elimination.

On the other hand, the Penalties for not satisfying part or all the demand should accommodate:

- The priorities among various competing users.
- The losses caused by the corresponding water shortage.

It may be emphasized that the Penalties caused by the water shortage do not express the same concept with the corresponding Benefits from the water use. Due to the acute character of water shortage, in many cases the supply cost is not seriously considered. Although the price of water usage is respectively high, its financial price does not reflect its worth neither it’s real cost, because it is considered as a renewable natural resource and a commodity. However, it is believed that a rational approach of this problem will effectively contribute into the sustainability of any implemented solution concerning the water shortage problem. The water price reaching the final consumers has to reflect its real cost and its usage value.The proper and rational quantification of the Benefits, Penalties and Costs could comprise the basis of rational water pricing.

Model Constraints

The model constraints impose limits on the problem variables and include:

The continuity equation in the water storage tank: $V_t = V_{t-1} + \sum_i F_{it} - \sum_j Q_{jt}$ (2)

Upper and lower bounds of the water in the reservoir: $V_{min} <= V_t <= V_{max}$ (3)

Capacity limitations of each supply scheme: $F_{it} <= S_{it}$ (4)

Flows allocated to each user should not exceed the corresponding Demands. Furthermore, it may be desirable to assign a minimum water quantity to some users.

$$Q_{jt}^{min} <= Q_{jt} <= D_{jt} \quad (5)$$

The resulting mathematical model is a Linear Programming problem that can be solved with any robust mathematical optimisation software. In case there are constraints in the model expressing decisions (e.g. selection of reservoirs, different water qualities etc.), then it will be a Mixed Integer Linear Programming model.

The software that has been used is GAMS that has been provided by our laboratories for the purposes of the project.

6. APPLICATION RESULTS

As an indication of the type of problems that can be solved and the type of the results that are expected, the proposed method has been applied in an island complex belonging to the Cyclades islands. The basic problem parameters are shown in Table 3.

More specifically, the case study under consideration is the island complex of Naxos province. Naxos is the largest of the Cyclades islands, with a population of almost 20,000 inhabitants and an area of 448 km^2. Naxos is surrounded by a number of smaller islands, called Mikres Cyclades that belong in the same province, namely the islands Heraklia, Schinousa, Donousa, Koufonisi, Amorgos. A map of the area is shown in Figures 3 and 4 and their water demands per user are shown in Figures 5 and 6.

Figure 3: Cyclades islands

Figure 4: The area under consideration

Naxos water supply sources are a dam with a capacity of 3 million m^3 water and a water ground reservoir with a capacity of 1,500,000 m^3. There is no water transport by boats and there is no water desalination unit on the island.

Naxos has a significant agricultural sector as well as stock raising activities. The total water demand for irrigation and stock raising is almost 10 million m^3 per year. In addition, Naxos has significant tourism and some industrial activities. The total water demand of the domestic-urban users of the island is almost 2 million m^3, while the distribution of the demand in the agricultural and urban sectors are shown in Figure 5.

Time horizon	12 months, time step 1 month
Water Users	Urban Use- Naxos, Irrigation Use-Naxos, Small Cyclades (Heraklia-Schinousa, Koufonisi, Donousa, Amorgos)
Water Demand	(Figure 5, Figure 6)
Water supply cost	C_{1t}= 3 €/m^3, C_{2t}= 4,4 €/m^3, C_{3t}= 7 €/m^3

Table 3. Case study data

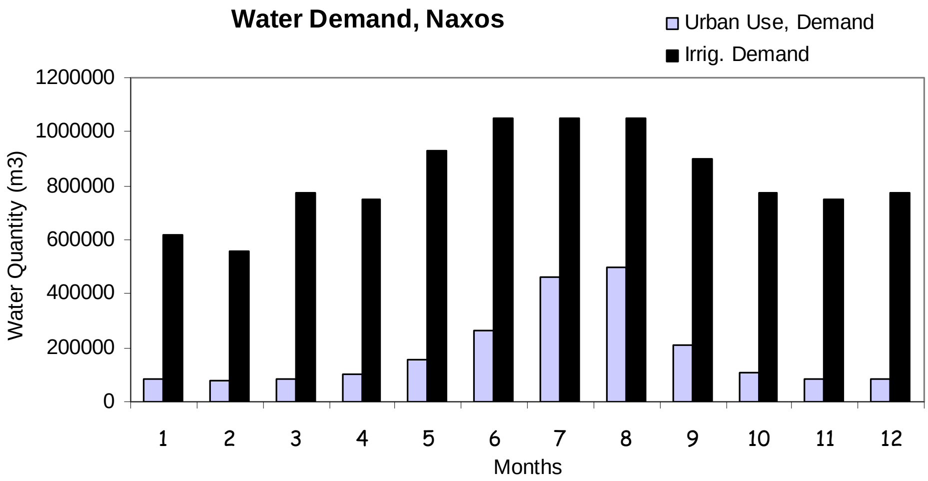

Figure 5: Water demand, Naxos island

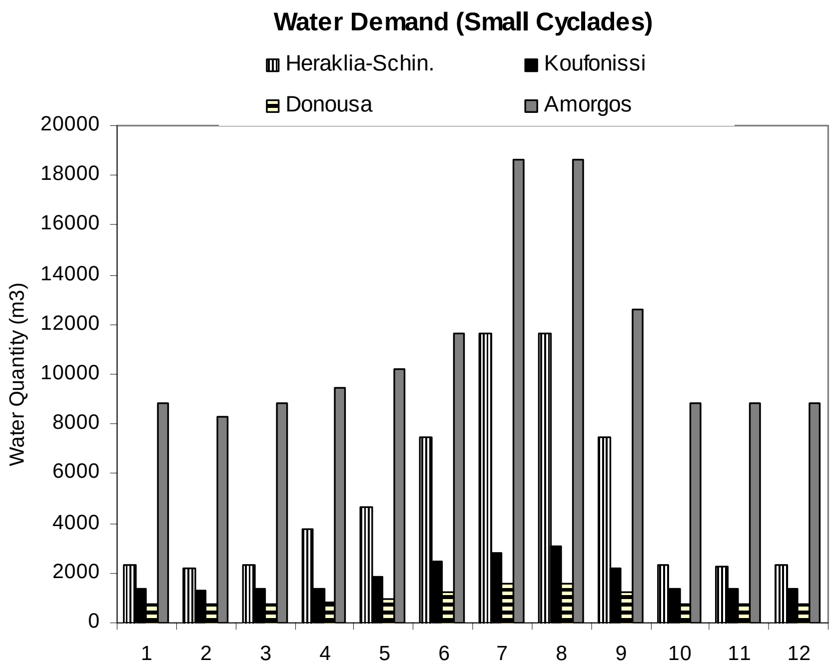

Figure 6: Water demand, Small Cyclades area

The type of results that the system will give are shown in Figure 7.

Depending on the relative values of the Benefits and Penalties for each of the users, the system may choose to satisfy fully the small surrounding islands needs and only partially the needs of the large island, at least as far as irrigation is concerned. Actually, this seems more rational, since the needs of the small islands are rather small and the water availability very critical for their development.

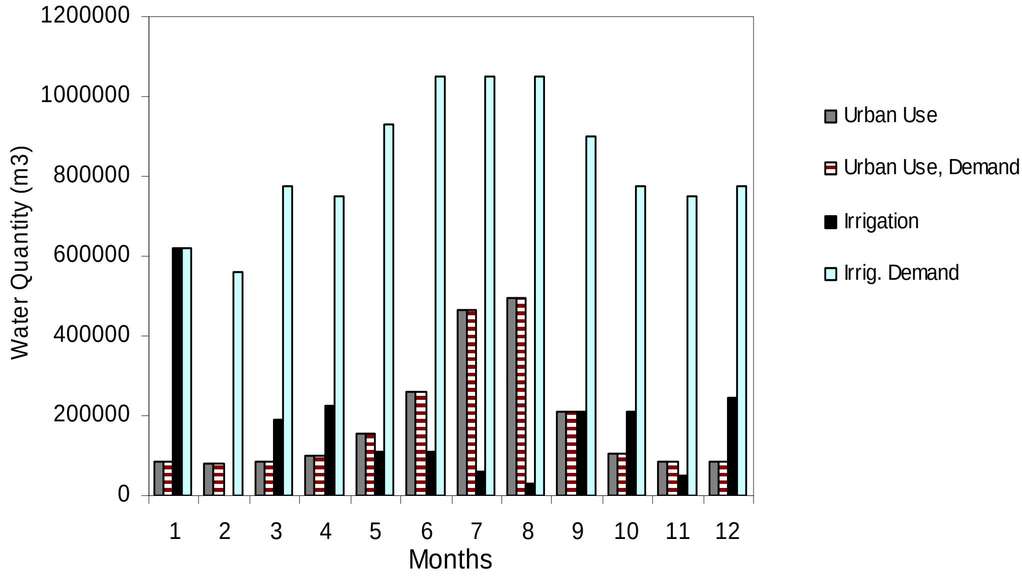

Figure 7: Results of water allocation in Naxos compared to demand

However, in other circumstances, there may be a partial and uniform satisfaction of water needs for all the users. In the results of the case study, all the demands of the Small Cyclades have been satisfied, as well as all the demands in the urban users of Naxos (Figure 7) and the irrigation demand has been partially satisfied, mainly because of the relative values of the Benefits and Penatlties that have been set in this particular problem.

7. CONCLUSIONS AND SIGNIFICANCE

The present work describes the value of Operations Research methods and tools in approaching and structuring water resources management problems. Furthermore, it analyses a project that has recently been carried out within the Archimedes Programme framework concerning the optimisation of water resources in areas with water shortage.

The proposed method for approaching this problem is the development of an optimisation model that takes into account complex water systems with multiple supply sources and multiple users and the possibility of total demand exceeding water availability. The water allocation is based on the new idea of assigning benefits to the water use, expressing the value that the water has to each user in a certain area and time period.

This approach of water systems planning provides the capability of an integrated study and investigation of the role of all the system parameters and gives a better insight to the problem of the optimal allocation of water resources, considering the value and priorities of the water usage. The resulting model is a mathematical programming problem, LP or MILP and may be of remarkable complexity; therefore a robust optimising software is needed.

The proposed approach is currently being implemented in a formal Decision Support System that could be proved very useful in geographical regions such as our islands. It will facilitate the decision making process by providing quantitative performance measures for the significance of each alternative solution and protect the sustainability of the water use.

Acknowledgment
This research has been conducted within the framework of the "Archimedes: Funding of Research Groups in TEI of Piraeus Programme", co-funded by the EU and the Greek Ministry of Education.

REFERENCES

1. S. Schreider, 2006, Operations Research Applications in Water Resource Management: Integration of Water Allocation and Economic Models, Proceedings, Applied Simulation and Modelling, Rhodes, Greece, 2006
2. Voivontas, D., Arampatzis G., Manoli E., Karavitis C., Assimakopoulos D., 2003, Water supply modeling towards sustainable environmental management in small islands: the case of Paros, Greece, *Desalination,* **156,** 127-135 .
3. Jacovkis, P. M., Gradowczyk, H., Freisztav, A. M. Tabak, E. G., 1989,. A Linear Programming Approach to Water-Resources Optimization. ZOR - *Methods and Models of Operations Research,* **33,** 341-362.
4. Froukh, M., 2001, Decision-Support System for Domestic Water Demand Forecasting and Management. *Water Resources Management,* **15,** 363–382.
5. E. Kondili, J. K. Kaldellis, 2007, Development and Operation of a Decision Support System for Water Management in Areas with Limited Water Resources, 14th International Symposium on Environmental Pollution and its Impact on Life in the Mediterranean Region, October 10-14, 2007, Sevilla – Spain
6. Kaldellis, J.K., Kondili, E., 2007, The Water Shortage Problem in Aegean Archipelago Islands. The Cost-Effective Desalination Prospects, *Desalination*, **216,** Issues 1-3, 123-138
7. Kondili E., Kaldellis J.K., 2006, Model Development for the Optimal Water Systems Planning, *Computer Aided Chemical Engineering, Volume 21, Part 2, 2006, Pages 1851-1856*
8. Kaldellis, J.K., Kavadias K.A., Kondili, E., 2004, Renewable energy desalination plants for the Greek islands—technical and economic considerations, *Desalination,* **170,** 187-203