WATER USE PLANNING WITH ENVIRONMENTAL CONSIDERATIONS FOR THE AEGEAN ISLANDS

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SUMMARY

The problem for the optimal water systems planning is tackled in this work, taking into account environmental considerations and sustainability issues related to the water sources and the water allocation to various users. The mathematical model that is developed integrates in a systematic way the benefits that can be expected from the water use and the costs of the various water supply methods. The model variables include the time varying water quantities supplied by different water sources and the also time varying water quantities being delivered to various users. The model parameters include the capacities of the water supplies, the different demands of the users, and the costs of each water supply method and the benefits of the water allocation to different users.

Model constraints express the demands, the limitations in the capacity of the various water sources, as well as technical specifications that must be followed in the water allocation. Criteria for the optimisation of the water planning and their corresponding mathematical expressions are proposed. The optimisation model highlights some interesting aspects of the water systems planning and operation such as the most efficient allocation of existing water supplies, even in cases of limited water availability.

KEYWORDS: Mathematical Modelling and Optimisation, Water Allocation, Water Systems Optimisation, Sustainability of Water Systems

1. INTRODUCTION AND BACKGROUND TO THE PRESENT WORK

Water is a constrained resource and in many areas of the planet water shortage is considered to be the most important problem. Actually the lack of fresh and of suitable quality water in an area practically prohibits its plan for development.

More than 25% of the world population lives in dry or semi-arid areas [1], the water supply chain management and optimisation is evolving as one of the most difficult and urgent problems [2].

The problem of the optimal water system design and planning is created mainly in cases where water is supplied from various different sources and needs to be distributed to users with possibly conflicting requirements. The unit cost of water is different for each one of the supply methods, and its value is different for specific allocation. The dimension of time plays a serious role in the problem, since the water's demand and availability, as well as all the other parameters vary significantly with time. Furthermore, the environmental factor should be incorporated in the definition of the problem and thus to avoid any unsustainable water supplies and allocations.

Several methodologies from systems engineering, particularly mathematical modelling, have increasingly been used over the last few decades for the optimal design, planning and operation of water resource systems. Optimisation models have also been applied for the solution of a number of problems related to the optimal planning of supply sources, or dealing with the total water resources management system [3-5]. However, limited research work has been carried out for the most difficult and urgent problem of the integrated water supply chain optimisation.

The present work approaches the water systems planning problem taking into account the characteristics of both, supplies and demands. Emphasis is in particular given to the environmental implications of water supply and water use. The methodology and the optimisation model proposed are generic and can be applied in any water system exhibiting relevant characteristics. For illustration purposes, special emphasis is given in the implementation of the model in the area of Aegean islands.

2. OVERVIEW OF THE WATER RESOURCES MANAGEMENT PROBLEM IN HELLENIC AEGEAN SEA

2.1 Water demand

Water is a constrained resource in many areas of the planet. Aegean Sea is an area with many varying size islands. Most of the Aegean islands suffer from severe lack of good quality fresh water, mainly because of the low precipitation and their specific geomorphology. Water supply shortage in the islands of Cyclades (a group of islands in the Central and Southern Aegean Sea) amounts annually to almost 5 million m^3 of water [1]. On the other hand, these places accept many tourists; especially during the summer period their population may be five times more than the winter population, thus resulting in more serious and acute water shortage problems. Figure 1 shows a typical daily water demand profile for an Aegean Sea island and its variation during the year.

Classification of the water consumption includes urban users (commercial, permanent and seasonal domestic users), industrial and agricultural users. However, in the area under discussion, water demand originates mainly from the agricultural and the urban users. Industry is not a significant water consumer in the islands.

The use and corresponding shortage of water in the urban and the agricultural sector, the water demand and availability and the water distribution in the two sectors in Cyclades islands are shown in Figures 2, 3 and 4 respectively.

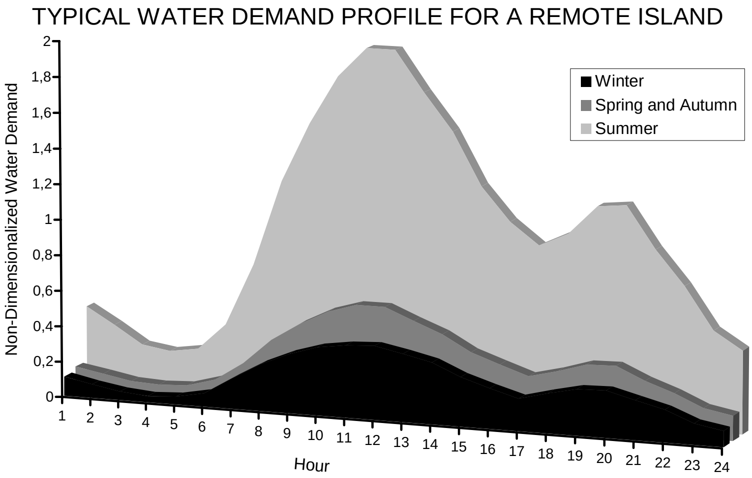

Figure 1. Typical water demand profile for a remote island

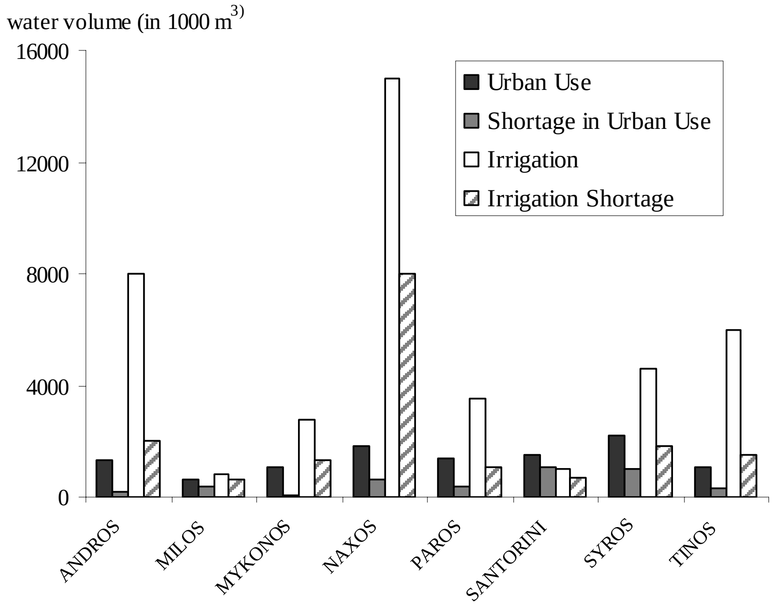

Figure 2. Water use and shortage in urban and irrigation sectors

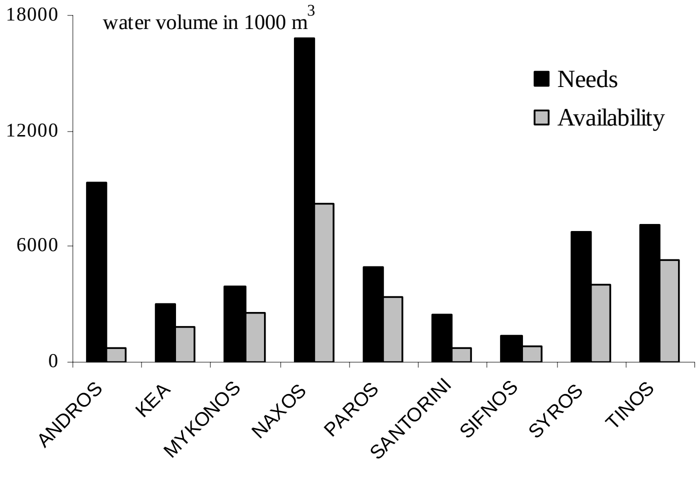

Figure 3. Water demand and availability in Aegean islands

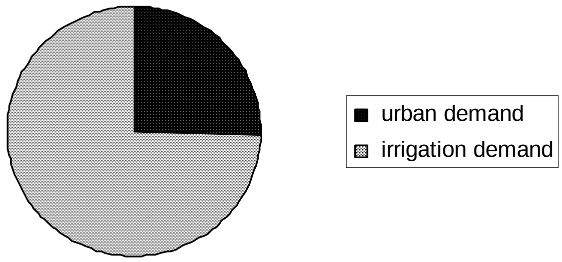

Figure 4. Average water demand distribution in Aegean islands

2.2 Water supply

The most common water supply sources in remote areas with limited water resources are the following:

- Ground reservoirs and dams associated with water treatment plants
- Desalination plants
- Wells and boreholes
- Water transfer with ships
- Water recycle and reuse (not commonly used yet).

For a long time, increasing water demand was covered by transfer through ships in the Hellenic islands. However, there are very significant economic costs associated with this method, as well as the faith that it is completely unsustainable and does not create any infrastructure for the long-term problem solution.

The resulting costs of water are different for each of the above sources. In practice, the cost includes a fixed term, associated to the depreciation of the capital investment and a variable cost term. The desalted water has a significant operating cost, while the water from ground reservoirs and dams has s serious fixed cost term, because of the high capital investment required. Figure 5 shows the different water costs for various sources [6].

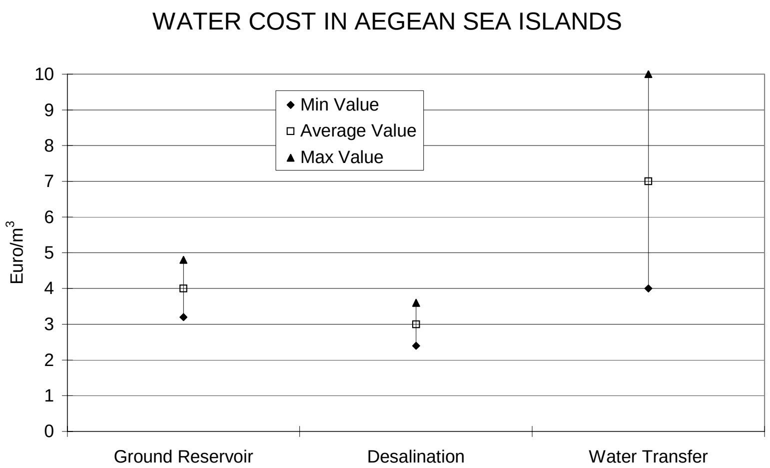

Figure 5. Water costs from various sources (ground reservoir: 200.000 m^3) [6]

3. SUSTAINABILITY ISSUES IN WATER SUPPLY AND USE

Water is a renewable natural resource. However, its availability depends highly on the season and the geographical region. In areas with shortage, water is overexploited and that affects seriously its quality and its future availability. Therefore, the planning process should take into account sustainability considerations in a consistent way and embed the environmental factor in the operation of the water system. In the present work, sustainability issues play an important role in the optimisation of the water system. Namely, the environmental factor is included in the proposed approach as follows:

- Water shortage is allowed in the system; i.e. there may be cases and certain time periods, when the water demand exceeds water availability. In this case, the resource allocation is done according to a predetermined set of priorities and some needs may be partially covered or not covered at all. Actually, this approach contributes substantially to the most efficient water allocation in contrast to the unsustainable way of continuously seeking new water resources for the satisfaction of the increasing needs.
- Water is supplied through various sources. However, some of them are very expensive and do not create any infrastructure for the future; for example, water transfer with ships. Assigning a high cost to this supply source, the system will avoid it unless the expected benefits from the allocation of the corresponding water quantities use exceeds costs.

4. THE PROPOSED MATHEMATICAL MODEL

4.1 Basic Characteristics and Structure of the Proposed Model

The mathematical model that is proposed in the present work identifies the optimal solution in the operation of the water system, taking into account:

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

The objective of the model is to determine the appropriate input flows from each supply source and the quantities allocated to each user, keeping in mind that the total water availability may be less than the total demand. Therefore, not all the demands will be covered. 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 [7]. 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 6 shows a schematic representation of the system under consideration.

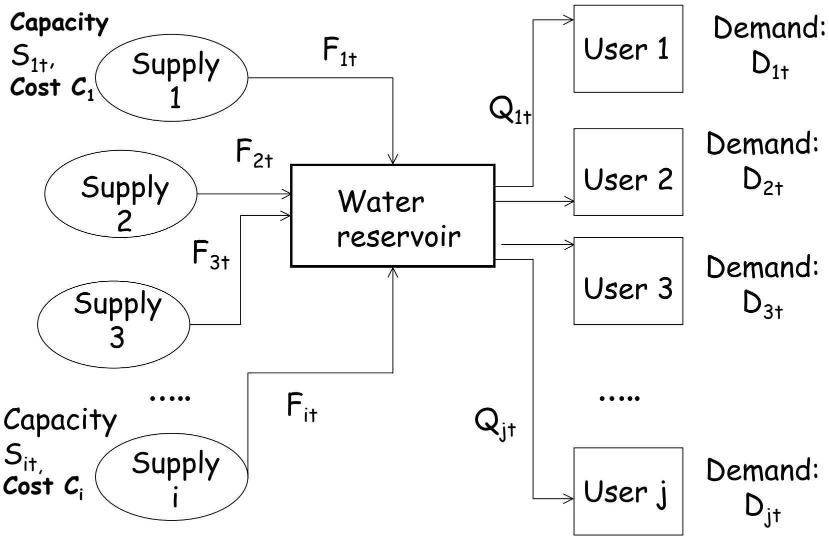

Figure 6. Schematic representation of the water system

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.

4.2 <u>Water Supply</u>

The usual supply sources taken into account in the present work are:

- Desalination units
- Ground Reservoirs and dams
- Water transfer by ships
- Own water resources (e.g. wells)
- Others

In fact the model can accommodate any type of water supply. The information that is required is its cost, capacity and any existing operational constraints.

The supply limits are determined from the capacity of each specific source. For the desalted water, the supply limit is the desalination unit's capacity, for the ground reservoir the supply limit is in practice the capacity of the water treatment plant, since in most cases the water from a reservoir needs to be treated before reaching the consumer. The ship transfers water into the storage tank at specific time periods. The capacity limit in this case is determined by the quantity that has been transferred by the boat.

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 [8]; the same is valid for the ground reservoir and the dam. On the contrary, the water transferred by ships has only a rather high variable cost term.

4.3 Water allocation

The users take water from the storage tank. The upper limits of the quantities being delivered to the various users are the corresponding time-varying demands.
The water users are:

- The agriculture (irrigation)
- The urban use (including permanent and seasonal domestic use and commercial use)
- The industry
- Other secondary uses.

In case the required water quantity exceeds the available one, not all the requirements will be satisfied. This will definitely cause some consequences to the users (e.g. cancellation or limitation of expansion plans, losses etc.). The allocation of water to users will be determined by the optimisation. However, 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 any case, the discrepancy between the allocated quantity and the demand should be penalised. Actually these penalties are expressed as extra 'costs' 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.

One of the most important dimensions of the present work is that environmental considerations should also be taken into account in the water allocation. The simplest way to achieve that is to assign high costs in the most unsustainable water supply methods. However, other more formal methods exist to take into account the environmental costs of each water supply method [9].

5. MATHEMATICAL MODEL DEVELOPMENT

5.1 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. Actually, the length of the time horizon will also indicate the time interval that will be the basic step for the optimisation model.

Parameter	Magnitude
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)
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)
C_{it}	Cost of water from supply source i at time interval t (€/m3)

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

5.2 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 including environmental benefit and costs, i.e.

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 including environmental costs.

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

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

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, a detailed study for the proper quantification of these Benefit magnitudes is needed. Actually these benefits should be reflected to the water pricing. On the other hand, the Penalties for not satisfying part or all the demand may express the priorities among various competing users.

5.3 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.

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

6. APPLICATION RESULTS

6.1 Case Study Characteristics

The above Mathematical Programming model is applied in a simple case study to illustrate the type of results that can be expected of this work. A typical island of Aegean Sea is considered. The basic parameters of the problem are shown in Table 3.

Time Horizon	Twelve months, time step: 1 month
Supply Sources	1:Desalination 2: Ground reservoir 3: Transfer by ships
Users	A: Urban, B: Irrigation
Demand Profile	Shown in Figure 7
Benefits	Shown in Table 4
V^{MAX}, V^{MIN}	1.000.000 m^3 and 10.000 m^3 respectively
Supply sources capacity	S_1=300000, S_2=200000m^3/month, S_3=1000000 m^3/year
Supply Costs	C_1= 3 €/m^3, C_2= 4,4 €/m^3, C_3= 7 €/m^3

Table 3. Data and basic assumptions for the case study

The effects of the following problem parameters will be indicated in this simple case study.

a) effect of the Benefits for each user

b) environmental considerations taking into account the costs of the unsustainable supply methods.

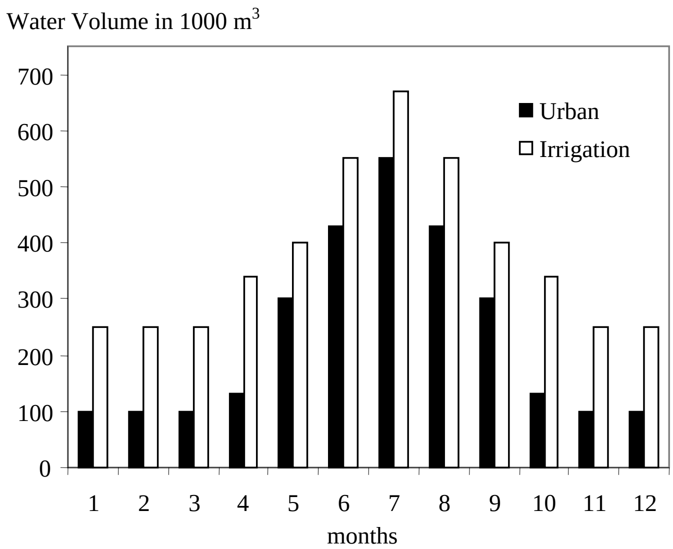

Figure 7. Demand Profile for the Case Study

6.2 Effect of Benefits

In order to isolate the effect of the water allocation benefits in the problem, it is solved taking the penalties for non-covering the demands equal to zero. Therefore, only the allocation benefits and the supply costs affect the problem solution.

The problem is solved for two cases:

Case A1: Initially the Benefits are shown in Table 4, where for user A (urban consumption) they are much higher for the summer months and for user B they are the same throughout the year

Months	1	2	3	4	5	6	7	8	9	10	11	12
B_{At}	5	5	5	15	20	25	25	25	10	5	5	5
B_{Bt}	5	5	5	5	5	5	5	5	5	5	5	5

Table 4. Benefits for the users of the Case study for twelve months (in €/m^3)

As shown in the results of Figure 8, the water is mostly allocated to the user with the highest Benefits. This also affects the water quantities that are stored in the storage tank. As shown in Figure 9, the water is stored during the winter months and is allocated to users in the months that the benefits are high.

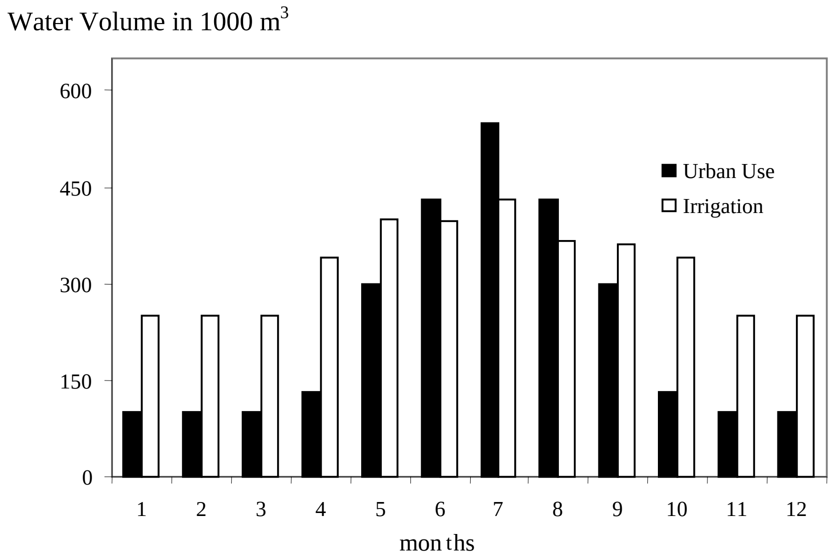

Figure 8. Model Results - Water distributed to users for Case A1

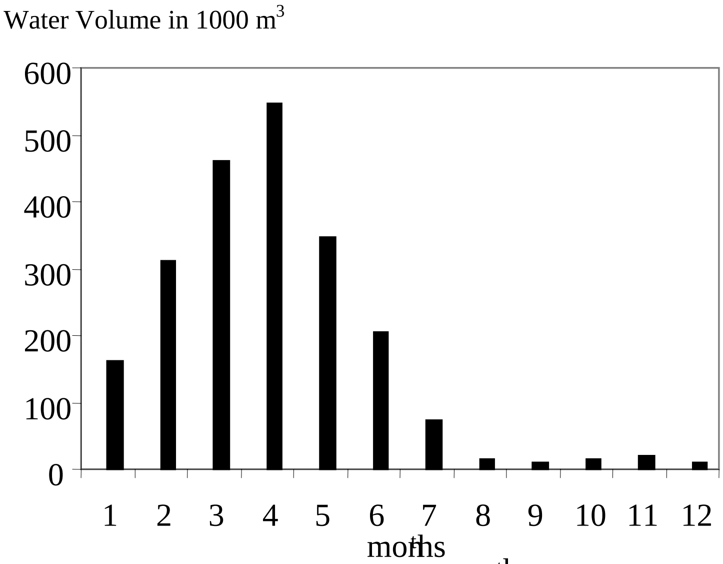

Figure 9. Model Results - Water volume in the storage tank for Case A1.

Case A2: Then the problem is solved with the Benefits being the same for both users throughout the year (Table 5).

Months	1	2	3	4	5	6	7	8	9	10	11	12
B_{At}	5	5	5	5	5	5	5	5	5	5	5	5
B_{Bt}	5	5	5	5	5	5	5	5	5	5	5	5

Table 5. Benefits for the users of the Case study for twelve months (in €/m^3)

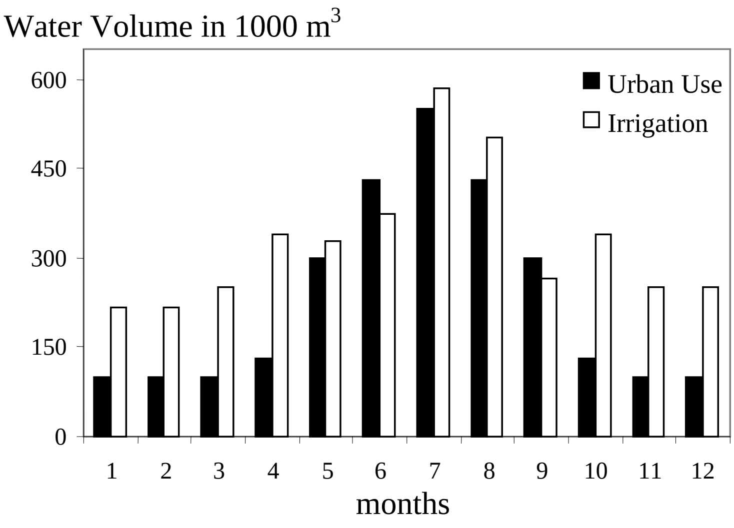

Figure 10. Model Results - Water distributed to users for Case A2

As shown in the above Figure 10, in this case the water allocation price follows the demand profile.

6.2 Effect of the Supply Costs

The problem is solved for the same demand profile as the one shown in Figure 7 and for two cases: In Case B1 the supply costs are:

C_1= 3 €/m^3, C_2= 4,4 €/m^3, C_3= 7 €/m^3

In Case B2 the supply costs are:

C_1= 3 €/m^3, C_2= 4,4 €/m^3, C_3= 10 €/m^3

The cost of the water from supply source 3 is more expensive in this case in order to indicate the effect of an unsustainable supply source, as is the water transfer by ships. It is noted that both Cases B1 an B2 are implemented with the Benefits taken as in Case A2 (all the same throughout the year).

The corresponding water supply quantities from the different supply sources are shown in Figures 11 and 12 respectively.

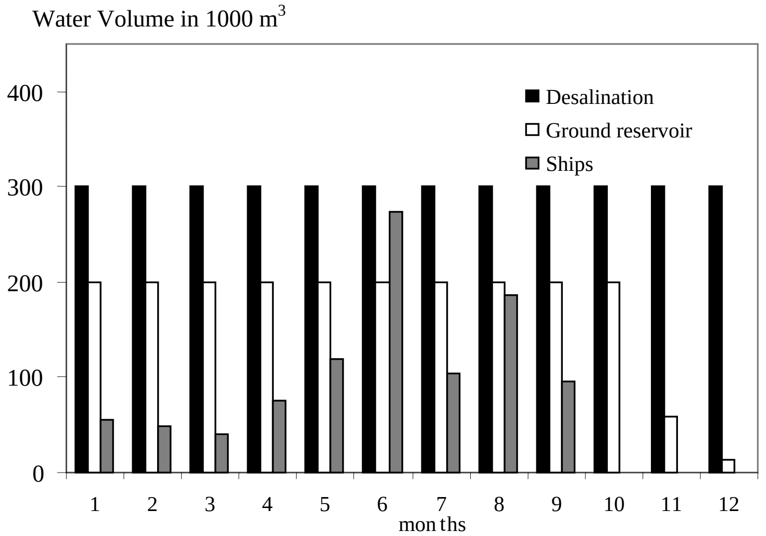

Figure 11. Model Results - Water supply quantities for Case B1

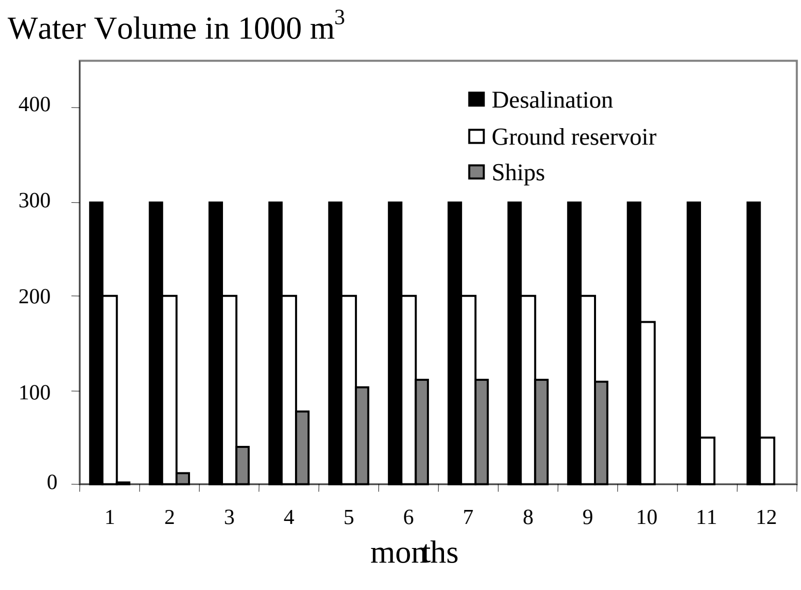

Figure 12. Model Results - Water supply quantities for Case B2

As shown in the above Figure 12, the optimisation has resulted in much less supply quantities of the expensive (unsustainable) source than the corresponding ones in Case B1. In Case B1 all the availabe quantity of water transferred by ships is finally transferred and delivered to the system (1.000.000 m^3), while in Case B2 the water quantity that has been transferred is 676,000 m^3 .

7. CONCLUSIONS AND SIGIFICANCE

An optimisation model has been proposed in order to carry out the optimal planning in complex water systems with multiple supply sources and multiple users, taking into account environmental considerations. The implementation of the resulting mathematical programming model evaluates the water flows from each supply source and the flows allocated to each user, in order to optimise an economic / operation efficiency criterion.

The model takes into account the costs of each supply source and the benefits from the water allocation to each user and allows the water availability to be less than the total demand. Thus, the work introduces the idea of optimally allocating the existing resources and eliminates existing inefficiencies rather than continuously seeking ways to expand the existing sources. Thus, environmental considerations are inherently taken into account in the operation of the system.

The systems engineering approach to the 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 various problem issues and to the analysis of the influences of different operating modes. The present study, being part of an ongoing research, provides a basis for further formal modelling. The model will be refined and extended in a number of ways and emphasis will be given in more formal ways to express environmental costs to each supply method. In addition, the behaviour of other supply sources such as the water reuse will be studied, which is another important and efficient method for water conservation.

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