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1. INTRODUCTION

Traditional water supply planning is based on fixed water requirements and the necessary mechanisms to deliver the water to meet those requirements (Medellín-Azuara et al., 2007). The rising costs to achieve 100% water supply reliability and the need for more sustainable management of scarce water resources have led to the well-known concept of Integrated Water Resources Management (IWRM). The concept of IWRM has been accepted internationally as a functional strategy for achieving efficient, equitable and sustainable development and management of the world´s limited water resources (UNDP, 2012). Moreover, taking into account the uncertainty of both global climate change and constantly shifting and expanding development patterns, a sustainable option to the water situation can only be achieved by an integrated approach (Grundmann et al., 2012).

In this context, optimisation is appealing in cases where problems (i) are clearly defined with quantifiable objectives, (ii) are describable using one or more mathematical models, (iii) have been analysed through the generation of a sufficient amount of available data to characterise the effects of alternative solutions and (iv) are without an obvious best alternative practice (Haith, 1982). Hence, optimisation techniques are a useful tool for water management policy analysis and strategic decision support (Cetinkaya et al., 2008).

Several optimisation models and multicriteria analysis have been developed with the intent of improving water management and planning. A detailed review of those models is presented by Liu et al. (2011) and Hajkowicz and Collins (2007). In spite of increasing interest in optimisation models, there remains a substantive need for further model development and refinement based on the IWRM concept. Since agriculture has traditionally been the main consumer of water resources, several optimisation models are primarily focused on optimal allocation of water in agricultural systems (Lu et al., 2012; Ortega Alvarez et al., 2004). More recently, non-conventional water resources have been integrated into the optimisation models (Lund et al., 2003; Ray et al., 2010).

To the best of our knowledge, only the researchs of Han et al. (2008) and Kondili et al. (2010) include multiple supply sources and multiple users. However, Han et al. (2008) presented an approach that employed multi-objective linear programming rather than wholly economic functions. Moreover, their model focused on city level issues, in contrast to the Directive 2000/60/EC (Water Framework Directive, WFD), which promotes management of water resources at the river basin level. The main limitation of the model developed by Kondili et al. (2010) is lack of consideration of a water distribution cost as an objective function, since the model assumes that users will take water directly from a storage tank.

Based on the concept of IWRM, a global optimisation model for water allocation has been developed which involves multiple supply sources and multiple users. The global optimal solution is guaranteed since the proposed model is an adaptation of the "generalized transport model". The model's aim is to maximise the value of the water considering all the revenues and costs associated with its use.

There are three main novel aspects that differentiate the proposed model from previous ones, those being the integration of i) the quality of the water from the supply and demand perspective, ii) the water losses or efficiency in the water distribution and iii) the existence of physical connections between supply and demand.

2. METHODOLOGY

Elements of the model

The proposed mathematical model takes into account various elements from both the demand and supply perspective. To make the model functional, each water source is characterized by a given quality, associating it with certain uses and some specific supply costs. It should be noted that the revenue generated for a specific water use is highly variable.

From the supply side, conventional and non-conventional water sources have been considered. Conventional resources include surface water (S) and groundwater (B). Non-conventional water sources include desalinated water (D) and reclaimed water (R). A third potential source of water comes from inter-basin water transfers (T).

From the demand side, four users have been considered for this model: i) urban (U), ii) industrial (I), iii) agricultural (A) and iv) livestock (L). Because water quality has been integrated into the model, not all water sources can accommodate all types of demand. In general, the four water users might be supplied with surface water, groundwater, desalinated water and water from transfers. Most of the international water reuse guidelines do not allow the use of reclaimed water for potable urban needs.

Objective function

The goal of the model is to maximize the benefits obtained from the use of water. Hence, the function to be maximized (Eq. 1 and 4) is the difference between total income and total cost. The optimisation problem should be solved for a certain time horizon which depends on the goal of the planner and the specific problem to be resolved. Model variables are shown in Table 1.

Variable	Description
Index j	Denotes each origin of water for the five sources
Index k	Denotes water each destination of water belonged to the three users
R_{kt}	Productivity of the water from user k at time interval t (€/m³)
Dem_{kt}	Demand of water from user k at time interval t (m³)
Def_{kt}	Deficit (demand not satisfied) of water from user k at time interval t (m³)
C_{jkt}	Cost of supplying water from origin j to destination k at time interval t (€/m³)
X_{jkt}	Water sent from the origin j to destination k at time interval t (m³)
P_{kt}	Penalization for not meeting the demand of the user k at time interval t (€/m³)
ME_{jkt}	Matrix of efficiency between the origin j to destination k at time interval t
MC_{jkt}	Matrix of connection between the origin j to destination k at time interval t
$AVAI_{jt}$	Water availability in the origin j at time interval t (m³)
Min_{jkt}	Minimum quantity of water that might be transported from the origin j to destination k at time interval t (m³)
Max_{jkt}	Maximum quantity of water that might be transported from the origin j to destination k at time interval t (m³)
Z_{jkt}	Binary variable of the use of the connections between origin j and destination k at time interval t
$Dmin_{ut}$	Minimum demand of water to be satisfied for urban use at time interval t (m³)

Table 1 Description of the model variables

While more efficient identification and allocation of water resources is instrumental in meeting demands, it is important to remember that in regions where water shortage is particularly acute, demand often exceeds supply, leaving some water requirements unsatisfied, resulting in a water deficit. Because the lack of water does not affect all users equally, many river basin management plans incorporate a supply hierarchy among water users. Moreover, there is inequality even within the same use category, that is, a water deficit can affect each user differently. For example, the economic losses caused by water shortage in multiannual crops are much greater than the losses suffered by annual crops. Therefore, the cost associated with water deficit for each use has been introduced in the model's objective function as penalties.

$$Max\ Ben = Total\ Income - Total\ cost \quad (1)$$

$$Total\ Income = \sum_{t}\sum_{k} R_{kt}\,(Dem_{kt} - Def_{kt}) \quad (2)$$

The total income gained from the use of water takes into account the productivity of the water (R_k) and the quantity of water used which is the difference between the demand (Dem_k) and the deficit (Def_k) in each destination.

$$Total\ cost = \sum_t \sum_j \sum_k C_{jkt}\ X_{jkt} + \sum_t \sum_k P_{kt}\ Def_{kt} \qquad (3)$$

The total cost involves two terms. The first one refers to the cost of supplying water from the origin j to the destination k. It includes delivery costs stemming from the construction and maintenance of water supply infrastructures such are canals, water reclamation plants and desalination plants. Transportation costs are also included in this first term. The second component of the total cost is referred to as the water scarcity cost. For each destination k, penalization (P_k) has been defined which takes into account the cost of not supplying all water demanded.

Based on equations (1), (2) and (3), the objective function is (Eq . 4):

$$Max\ Ben = \left[\sum_t \sum_k R_{kt}\ (Dem_{kt} - Def_{kt})\right] - \left[\sum_t \sum_j \sum_k C_{jkt}\ X_{jkt} + \sum_t \sum_k P_{kt}\ Def_{kt}\right]$$

(4)

where:

$$j = \{r_1, \dots, r_{nr}\} \cup \{s_1, \dots, s_{ns}\} \cup \{b_1, \dots, b_{nb}\} \cup \{t_1, \dots, t_{nt}\} \cup \{d, \dots, d_{nd}\}$$

$$k = \{a_1, \dots, a_{ma}\} \cup \{i_1, \dots, i_{mi}\} \cup \{u_1, \dots, u_{mu}\} \cup \{l_1, \dots, l_{ml}\}$$

An aspect that should be considered is the physical connection between water's origin and its destination. The lack of a physical connection means that all destinations cannot be supplied by all origins. For example, regenerated water is usually used to supply those needs that are closest to the water regeneration plants. This connectivity is defined as a matrix of connection (MC_{jkt}). It is a binary matrix given a default value of either 0 when there is no connection between the origin *j* and the destination *k*, or 1 if a connection exists.

No water transport system is without a certain number loss points due to leakage (old infrastructure tends to lose more than newer equipment) and evaporation. These losses ensure that not all of the water initially sent from the origin *j* arrives at its destination *k*. In order to integrate losses into the optimisation model, a matrix of efficiency $(ME_{jkt}$) has been defined. It represents the percentage of water sent from the origin *j* arriving at destination *k*. For estimating the total cost of supplying water, the variable used is the quantity of water sent (X_{jkt}), and the income is calculated based on the quantity of water that arrives at the destination $(Dem_{kt} - Def_{kt})$ (see Eq. 6).

Constraints

Water availability constraints:

There are two main constraints relative to water availability: i) the sum of the water sent from each origin to different destinations cannot exceed the resource availability at each origin (Eq. 5) and ii) the quantity of water that arrives at destination *k* is equal to the sum of water sent from the different origins *j* to this destination, taking into account the efficiency of the water distribution system (Eq. 6).

$$\sum_{t}\sum_{k} X_{jkt}\, MC_{jkt} \leq AVAI_{jt} \qquad \forall j,t \qquad (5)$$

$$\sum_{j} X_{jkt}\, ME_{jkt} = Dem_{kt} - Def_{kt} \qquad \forall k,t \qquad (6)$$

Technical constraint:

The model must take into account the minimum and maximum capacities of both the physical connections between sources and destinations and the very existence of a connection (MC_{jkt}). The volume of water sent from origin *j* to destination *k* must fall between the minimum and maximum capacities of the connection.

$$Min_{jkt}Z_{jkt} \leq X_{jkt}MC_{jkt} \leq Max_{jkt}Z_{jkt} \qquad \forall k,t \qquad (7)$$

Legal constrain:

Legislation (national, regional or local) regarding the urban water supply often establishes a minimum amount of water to be supplied per person, per day. While this is basically a public health issue, it must be considered in the model since it establishes a potential minimum volume. The quantity of water that arrives for each unit of urban demand $(Dem_{ut} - Def_{ut})$ must be equal to or higher than the legal requirement $(Dmin_{ut})$.

$$Dmin_{ut} \leq Dem_{ut} - Def_{ut} \qquad \forall u,t \qquad (8)$$

The proposed model assumes constant costs for each origin independent of the quantity sent to each destination. Since water supply infrastructures are affected by economies of scale, a more realistic option will be the use of a variable, or tiered, pricing structure. In doing so, an alternative routine would incorporate demand curves (therefore, prices) by adjusting to different levels. This is accomplished by the use of quasilinear functions that can be modeled using binary variables. This approach has the potential for a wider range of applicability than the incorporation of nonlinear functions since these problems (continuous or entire) do not guarantee a global solution. Hence, it would be very difficult to solve the problem particularly if the model includes entire variables since entire and not linear problem would be encountered.

3. RESULTS

The developed model was applied to the Pinios River Basin. It includes 20 urban demand units (UDU), 21 agricultural demand units (ADU), 11 industrial demand units (IDU) and 19 livestock demand units (LDU). The main objective of this case study was to compare the current water allocation regarding the optimal allocation based on the economic model previously described. The study was carried out at demand unit level allowing maximize the use value of the available water in the watershed.

Figure 1 gathers the current and optimal water allocation for each demand in the Pinios River Basin. At aggregate level, it is illustrated that for urban units the current water allocation is the optimal one. Moreover, it is shown that, according to the economic optimization model, the water allocated for irrigation purposes should be slightly lower than the current which would increase the quantity of water available for industrial and livestock uses.

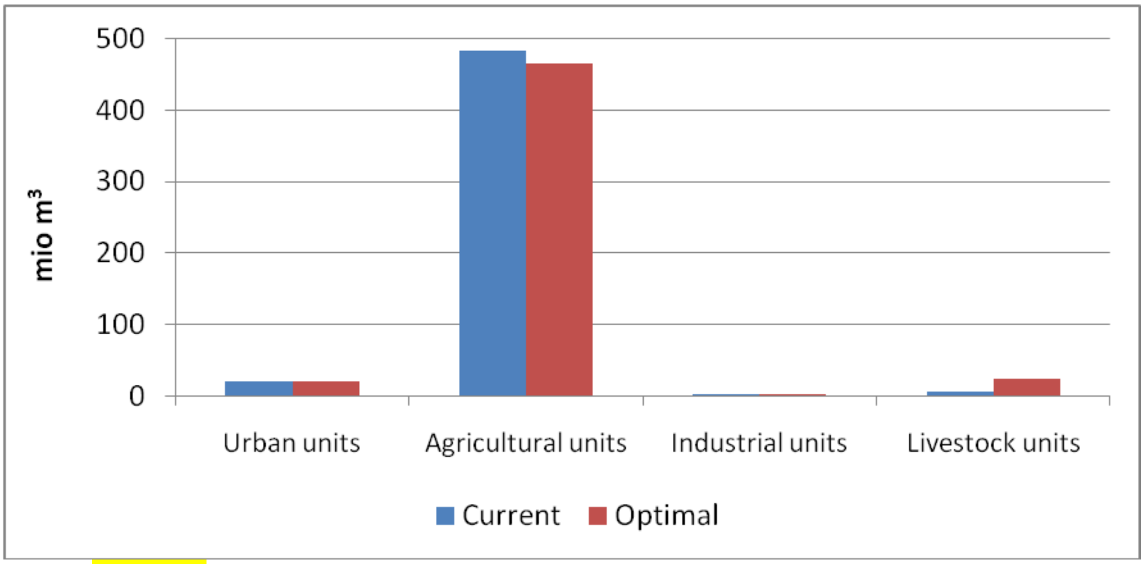

Figure 1. Current and optimal water allocation in the Pinios River Basin

When considered each water use at unit level, more detailed information is obtained. The current water allocation is optimal for all the UDUs embracing the Pinios River Basin (Figure 2). Regarding ADUs, Figure 3 shows that in 9 of the 20 units the actual quantity of water used is higher than the optimal from an economic point of view while in the remaining 11 ADUs the situation is the opposite, i.e., they have less water than the optimum. In the case of the industry (Figure 4), the divergence between the current and the optimal water allocation is minor for all units except for the unit number 11 since for this unit the optimal quantity of water to be allocated is more than double than the current one. Nevertheless, it should be noted that this difference is just 1 hm³. More important are the differences between the current and the optimal water allocation in the LDUs. It should be noted that in 14 of the 19 units the quantity of water supplied at this moment is lower than the optimal (Figure 5).

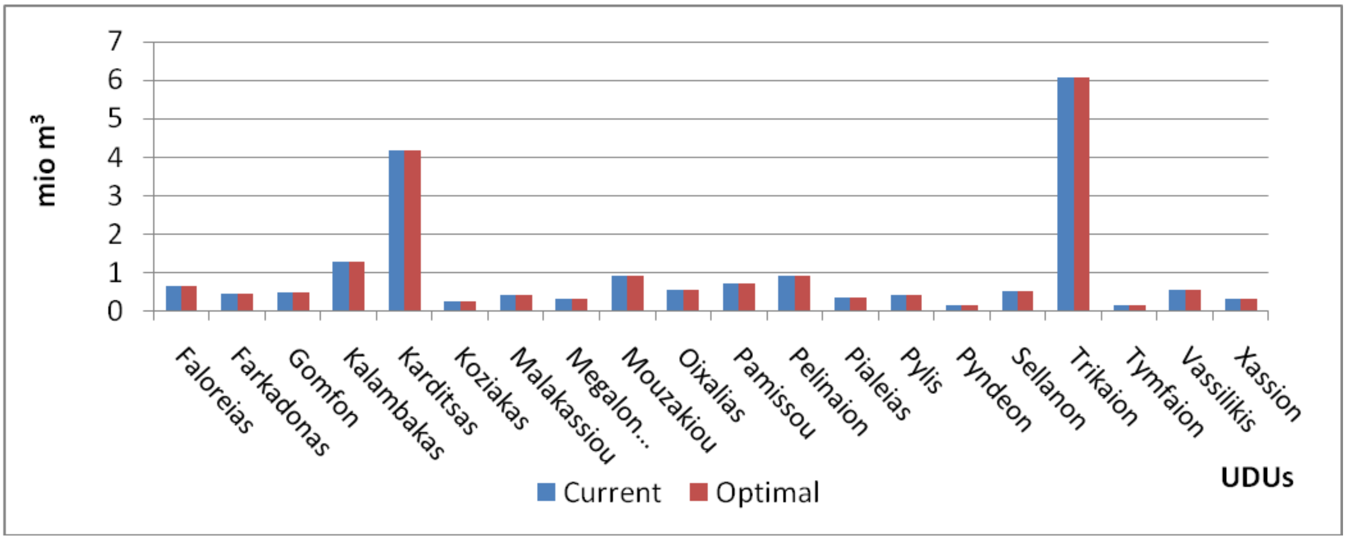

Figure 2. Current and optimal water allocation for urban demand units in the Pinios River Basin.

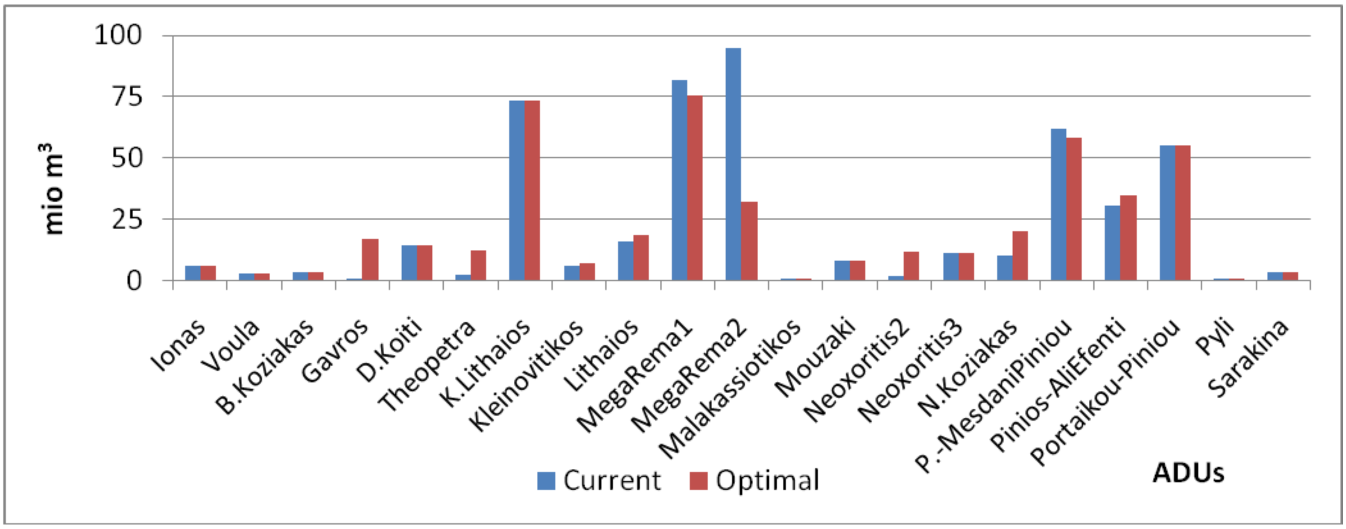

Figure 3. Current and optimal water allocation for agricultural demand units in the Pinios River Basin.

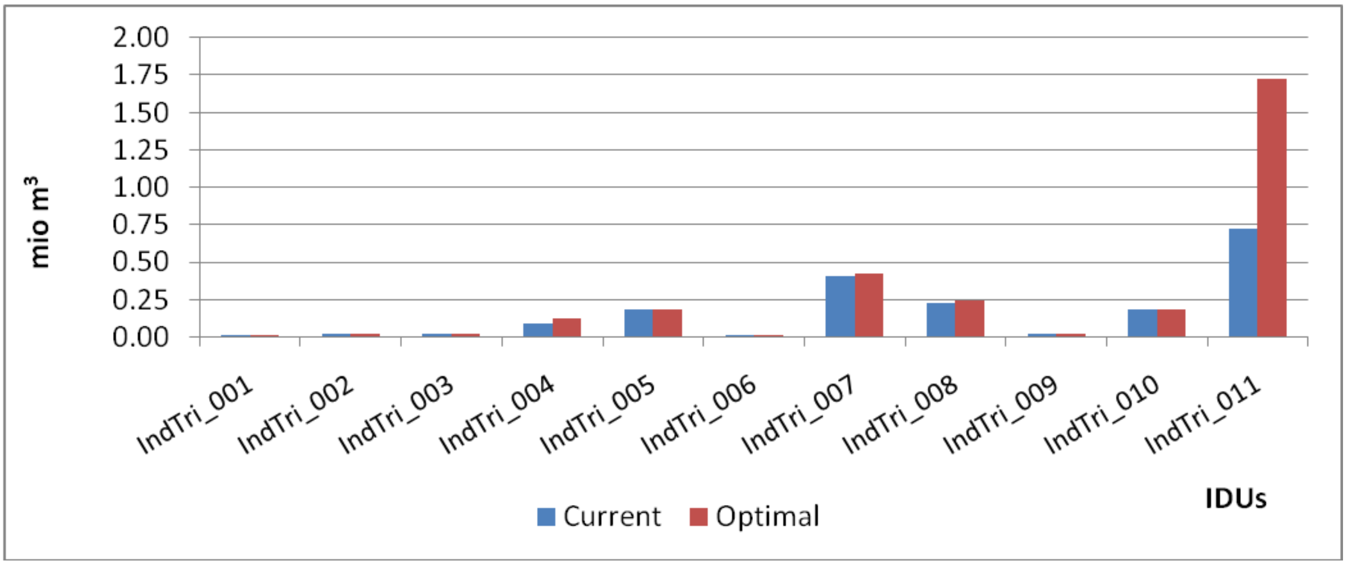

Figure 4. Current and optimal water allocation for industrial demand units in the Pinios River Basin.

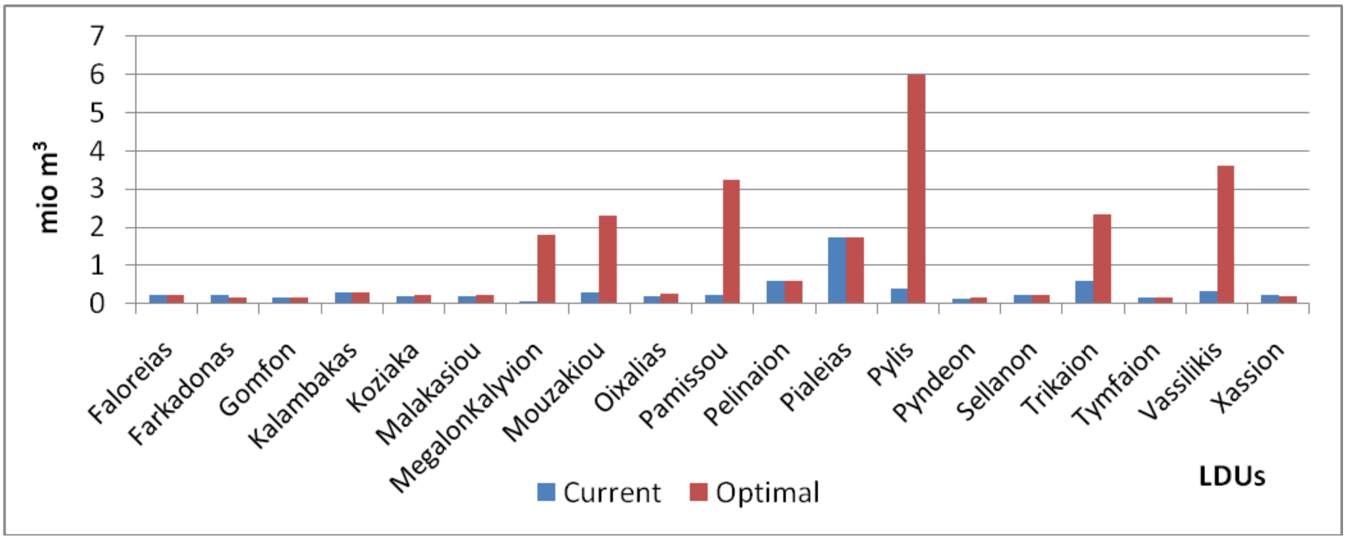

Figure 5. Current and optimal water allocation for livestock demand units in the Pinios River Basin.

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