Modelling water resource allocation: a case study on agriculture versus hydropower production

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MODELLING WATER RESOURCE ALLOCATION: A CASE STUDY ON AGRICULTURE VERSUS HYDROPOWER PRODUCTION

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ABSTRACT

In this paper we propose an economic model for the optimum allocation of water within a given area with the following features. First, the introduction of the institutional, geographical and time scheme under which the water rights are granted. Secondly, the establishment of a modelling framework for these characteristics which influence and are, in turn, influenced by two particular circumstances, namely the irregular conditions of the upstream flows and the possible new requirements of some of the users. Particular attention is paid to the influence of the time and space variables on both the water demand and supply conditions. The application of the model to a specific case confirms the potential of the analysis as a basis for achieving improvements in water allocation from the former administrative-based rules to new flexible and tradable water rights. In both case, gains are obtained from the exchange and we can note the implications of the time and space variables on the optimal allocations.

KEYWORDS: Water Rights, Agriculture, Hydropower, Allocation, Efficiency.

1. INTRODUCTION

The problems associated to the management of water in Mediterranean climates are well known, with these essentially resulting from the uncertainty associated with the supply of water in terms of both space and time. Thus, in order for users to be guaranteed the possibility of counting on the necessary surface water resources, volumes and priorities are allocated to different uses by way of water rights. These rights represent the main legal instrument that ranks and shares the uses with respect to space and time.

As Howe et al. (1986) have stated "property rights in water can be completely described only by a definition covering the quantity diverted and consumed, timing, quality and places of diversion and application. Changes in any of these characteristics could potentially affect other water users". With this being the basic scenario within which water users operate, the literature contains various studies that place emphasis on the need to introduce flexibility in the allocation of resources. In this sense, the now classic work of Coase (1960) demonstrates that, once property rights have been established, their exchange by the agents would generally lead to improvements in the Pareto sense. For the particular case of water, the works of Young and Haveman (1985), Gibbons (1986), Howitt (1988), or that of the earlier mentioned Howe et al. (1986), are illustrative of how proximity to market situations leads to more efficient allocations of the resource.

The correct definition of water rights (in the terms described above) and of third parties -particularly of the environment- are two of the main problems to which the literature has also given attention. In this regard, Winpenny (1994) carries out an in-depth analysis of the difficulties implied in these definitions and notes that the allocation of water throughout the world is carried out by way of administrative rules, with the market approach being the exception.

In any event, when beginning from the basis of clearly inefficient allocations of the resource, there is an important margin for transactions that would markedly improve this situation. In this line, it is possible to propose allocation systems that, taking into account environmental, institutional and hydrologic restrictions, lead to exchanges that are beneficial for society as a whole.

Against this background, the aim of this paper is to demonstrate how, for a specific case, incentives can make the existing bureaucratic resource management more flexible. Just as in the works of Houston and Whittesey (1986), Butcher and Wandschneider (1986) or Chatterjee el al.(1998), the allocation problem we consider arises out of competition for the water resource between two users, namely agriculture and hydropower. The novel aspect of our work is that the proposed model and the resulting optimum allocation take into account two aspects of Howe's concept of the definition of water rights that have not, in our view, received sufficient attention, i.e. timing and place of diversion[1].

These two important aspects will be reflected both in the way the problem is framed and in the main results. Specifically, the problem we are considering is water allocation between users situated in different locations and with requirements at different times of the water year. On this basis, we examine whether it is possible to obtain benefits from a hypothetical bilateral exchange.

Obviously, the fact that we focus on incentives to transactions does not mean that these actually take place. Such exchanges depend to a large extent on legal, hydrologic and, mainly, historical settings. In Spain, for example, the allocation of water is carried out by way of rigid administrative mechanisms and at prices that hardly reflect the transport and water storage costs. If, to all this, we add that expectations of new supplies of cheap water are constantly being raised by the Public Administration, then it should come as no surprise that the users show only limited interest in transactions which suppose, at the very least, that they have to pay the opportunity costs of the activity which assigns its rights (see Sumpsi et al.,1998). Nevertheless, we agree with Howe et al.(1986) that it is necessary to demonstrate specific situations of Paretian improvements derived from the exchange in order to convince both policymakers and users of the advantages of these types of systems, as compared to the traditional subsidised supply of new resources.

It is in this context where the time and space dimensions acquire a particular relevance. The current administrative system establishes a series of priorities that are independent of time and space. In this sense, new demands by any user affect the whole system and the way in which water is available for the remaining users can therefore be restricted, depending on where and when the water is required. For example, the current plans for the transfer of water from the Ebro to the Mediterranean basin have been drawn-up with little account being taken of the effects on the time and space distribution of the flows in the basin from which this water is to be transferred. This could result in the disappearance of the Ebro delta, which requires certain minimum stream flows at specific times.

The rest of the paper is organised as follows. In Section 2, we consider the model that underlies our specific case study. This model includes the specification of the behaviour of two users and the formal representation of the priority of water rights which results from applying current legal regulations. Particular attention is paid to the geographical and time characteristics of these rights. On the basis of a restricted optimisation model, we show that it is possible to obtain an efficient allocation that leads to greater joint profits. Section 3 is devoted to a calibration and empirical application of the model through a simulation of two scenarios: drought and extension of arable land. Section 4 closes the paper with a review of the main conclusions.

2. AGENTS, VARIABLES AND OPTIMISATION FRAMEWORK

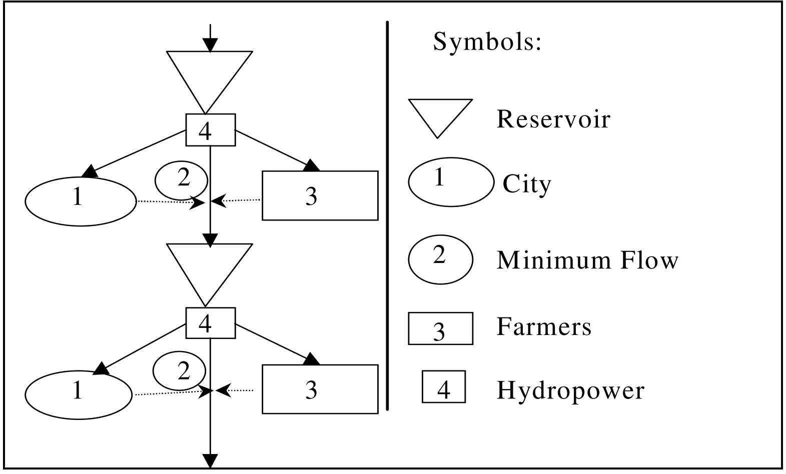
In this Section we propose a model on the basis of which it is possible to obtain water allocations between users. Our aim is to construct this model in such a way that it covers the largest possible number of situations. However, before discussing the model in detail, let us first consider the agents who intervene, their geographical location and the initial institutional and hydrologic framework.

2.1 The agents

As we can see from Figure 1, we consider two reservoirs upon which four types of agent, namely cities, minimum instream flow for environmental reasons, farmers and hydropower depend. The water rights of each of these agents are restricted by the maximum volume that can be used, at any moment in time and by a strict order of priority in the following terms. First, the city users are supplied with a maximum security level. This supposes that there is a prior level of reserves in the reservoirs that cannot be used unless and until the city uses have been satisfied.

Once the drinking water needs have been covered in the above terms, it is necessary to guarantee the minimum flow, which consists of a minimum continuous flow in the natural channel. The next use under this order of priority is that of agriculture. In contrast to the two earlier uses, this requires water for only half the water year, that is to say, during the irrigation period. It is this aspect that gives relevance to the time distribution of the rights and to the possibilities for the transfer of resources from one time period to another through storage in reservoirs. For the sake of simplicity, we consider only two sub-periods in the water year, namely, the irrigation and the non-irrigation periods.

Figure 1



The last agent to appear under this order of priorities is hydropower, in the form of the hydroelectric plants located at the foot of the reservoir. These plants release water only when the other uses are satisfied in each period. Once all the other users have received the amount of water established in their water right (hereafter referred to as "allotment") it is possible to accumulate water in the reservoirs in prevision for possible drought periods and until their storage capacity is reached.

All the agents are organised spatially around two systems (upstream and downstream) regulated by two reservoirs that, logically, are interdependent. A scheme established in this way describes a large number of situations that could be represented as particular cases of it. The interdependencies translate into two aspects: first, the agents located downstream are, to some extent, subsidiaries of their homologues and of the upstream priority uses; secondly, the reservoirs are managed in a co-ordinated manner in order to meet the needs of the totality of the users.

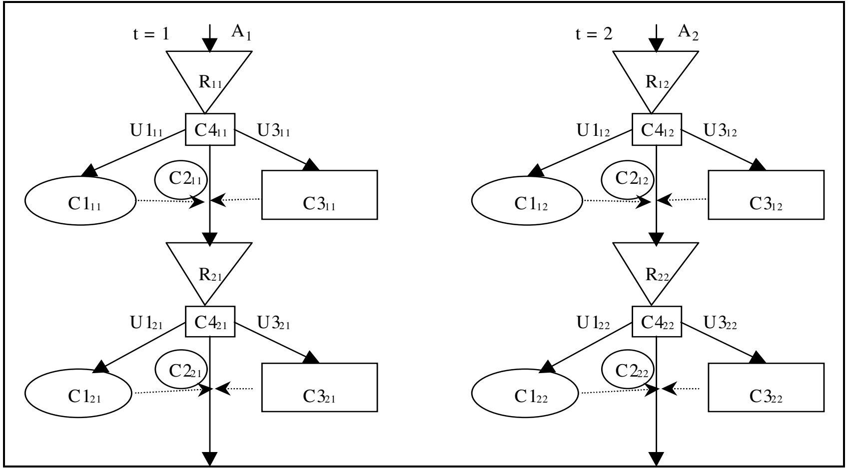
For practical purposes, we assume that the city and environmental requirements are given and, whenever possible, coincide with the allotment. By contrast, we assume that both farmers and hydropower have a profit function that depends on the volume of water used. This means that the requirement of the cities and the minimum flow act as mere restrictions, whilst the water used by farmers and hydropower are our main variables.

2.2 Variables

The allotment (maximum quantity established in the water right) and effective applied water levels are represented by Ck_{jt} and Uk_{jt}, respectively, with k = 1, 2, 3, 4 types of use; j = 1, 2 systems and t = 1, 2 sub-periods of the water year mentioned above. We denote by R_j^0 the minimum levels of the reservoirs dedicated to guaranteeing drinking water.

Two important state variables of the model are V_{jt} and R_{jt}. V_{jt} represents the volume of water supply per period in each system and corresponds to the initial reserves (R_{jt-1}), plus the quantity of water it receives, either in the form of the natural upstream inflows of the river (A_{jt}) or from the earlier return flows[2] (rk_{j-1t} Uk_{j-1t}), with rk_{j-1t} being the rate of return flows of use k in system j-1 and in period t . Thus, there are two flow variables (C, U) and three state variables (R, A, V)[3].

Figure 2



As regards the variable R_{jt} (reservoir reserves of system j at period t), this takes values between 0 and the maximum capacity of the reservoir (R^{max}). Furthermore, and in function of whatever is the amount of the upstream flows and the intensity of the uses, it will take values above or below the security reserve R_j^0. Thus, if the available water is insufficient even for urban uses, the reserve will be null until these are satisfied and, thereafter, these reserves will have priority over any other use until such a security level ($R_{jt} = R_j^0$) is reached. Once this limit has been exceeded, additional units of water will be kept in the reservoir only if all the other uses are satisfied. These variables, their spatial location and time distribution are presented in Figure 2.

2.3 The model

Farmers cultivate a mixture of i different products (i = 1, 2, ..., n) with net profits per unit of surface area (with the cost of water also being discounted) of $m^A{}_{ij}$, surface areas per crop of s_{ij} and applied water for each crop and irrigated area of $U3_{ijt}$ (which, in turn, depends on the water needs of the crop (NH_{ij}) and the irrigation efficiency (e).

With respect to the hydropower plant, the profit also depends on its unit margin (m^H), on the released flow ($U4_{jt}$), on a conversion independent of these factors in energy, which we denote as α, and on the head of water in the reservoir (h_j) which, in turn, depends on the volume stored in the reservoir $h_j = h_j\ (R_{jt})$. The margin m^H corresponds to the profit obtained by the last unit of energy (Kwh) produced.

The restrictions reflect the two aspects we consider to be essential, that is to say, the water right system and spatial location, with the first of these establishing the order of priority, the allotment and the moment in time at which the use becomes effective.

In function of these criteria and of the places of diversion, we have two possible relationships between the uses: rival and successive (or non - rival). Two uses are rival if they compete for the same unit of water in the same place (although they do so at different moments in time). By contrast, two uses are successive if the withdrawal of one unit of water on the part of one of them does not prevent its use by the other.

Under this general scheme, we can propose a model of optimum allocation between the uses with the following objective joint profit function and restrictions:

$$\text{Max M} = \sum_{t=1,2}\sum_{\text{j}=1}^{2}\sum_{\text{i}=1}^{\text{n}} \text{m}_{\text{ij}}^{\text{A}}\ \text{s}_{\text{ij}}\text{U3}_{\text{ijt}}(NH_{ij};e_{ij}) + \text{m}^{H}\ \alpha \sum_{\text{t}=1,2}\ \sum_{\text{j}=1}^{2}\text{h}_{\text{j}}(\text{R}_{\text{jt}})\,\text{U4}_{\text{jt}}$$

subject to:

$$V_{jt} = R_{jt-1} + A_{jt} + V_{j-1t} - (1 - r1_{j-1t})U1_{j-1t} - (1 - r3_{j-1t})U3_{j-1t} - R_{j-1t} \tag{1}$$

$$\begin{aligned} R_{jt} = {} & Min\{R_j^{\max}; Max[V_{jt} - Max(C4_{jt}; C1_{jt} + C3_{jt} + \\ & Max(C2_{jt}; Max(C4_{j+1t}; C3_{j+1t} + C1_{j+1t} + C2_{j+1t} - R_{j+1t-1}))); \\ & Min(R_j^0; R_{j+1t-1} + V_{jt} - U1_{jt} - U1_{j+1t}; V_{jt} - U1_{jt})]\} \end{aligned} \tag{2}$$

$$U1_{jt} = Min\{C1_{jt}; V_{jt}\} \tag{3}$$

$$U2_{jt} = Min\{C2_{jt}; V_{jt} - U1_{jt} - R_{jt}\} \tag{4}$$

$$U3_{jt} = Min\{C3_{jt}; Max\lfloor 0; V_{jt} - U1_{jt} - R_{jt} - Max\lfloor U2_{jt}; U1_{j+1t} + U2_{j+1t} - R_{j+1t-1}\rfloor\rfloor\} \tag{5}$$

$$U4_{jt} = Min\{C4_{jt}; V_{jt} - R_{jt}\} \tag{6}$$

The relationship between effective uses and water rights (priority and volumes) are reflected in the restrictions in the following terms: the water used by a set of successive uses will be the highest of all of them, whilst from amongst a group of rival uses, it will be their total. For example, in restriction 5 we can see how $U2_{j,t}$ and $U1_{j+1,t}$ are successive uses, whilst this $U1_{j+1,t}$ is a rival offstream use with respect to $U2_{j+1,t}$.

Furthermore, the order of priority is reflected in the fact that, for each activity, the water used will be the total available volume (Vjt), minus the sum of the amounts consumed by rival offstream uses which have a priority over that activity. In any event, any user can apply more water than the allotment established in its water right. This last aspect justifies that initial minimum option of restrictions 2 to 6. Given that we have two systems, the variables in j+1 and j-1 are null for j=2 and j=1, respectively.

The spatial structure is also implicit in the restrictions, i.e., between two users of the same type, the user which is located further upstream will have priority. Furthermore, the state variable R_{jt} takes into account all the requirements located downstream. Thus, the demands of system 2 condition the available reserves in the whole system at any given time.

As we can note, the level of joint profit depend both on the volume of supply of water and on the time and spatial structure of the water rights. More detailed information about the behaviour of reserves and joint profit function for different availability of water can be obtained from the authors upon request.

On this basis, we are in a position to carry out a comparative analysis with the following steps. First, we define a starting point situation according to which, for the sake of simplicity, the supply and the requirement coincide exactly in space and time. This is the situation that arises in the case where the supply of water is exactly that necessary in order to satisfy all the water rights under the terms and in the places established. Secondly, we suppose a change in the initial conditions in two directions: a fall in water supply (drought) and an increase in agricultural requirements. We then evaluate and compare the two allocations, namely, that resulting from the strict application of the current water rights and that resulting from the joint profit optimisation exercise.

3. APPLICATION OF THE MODEL TO A CASE STUDY

In this Section we apply the model in order to represent and solve two specific water allocation problems. Our case study rests on two types of data: that of system 1, which is real and has served to calibrate the model, and that of system 2, which is simulated.

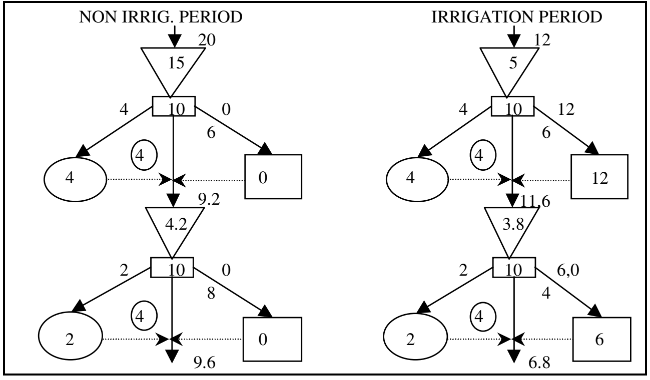
3.1. The starting-point situation

The starting data for system 1 come from the Vadiello reservoir, located in North-eastern Spain. The requirements are well delimited in this area, as can be seen from Figure 3. Data about these requirements were obtained from CHE (2000) and MAPA (1999). Furthermore, the security reserves for urban use are 5 and 2.5 Hm^3, respectively, in each system, whilst the maximum capacity of the reservoir is 16 Hm^3 in the two cases. The second system is simulated on the basis of data from the first, considering that its demands are one half (except for the minimum flow, where it seems reasonable to assume that this will be the same throughout the length of the river). The data on cultivated surface area and agricultural profits have been taken from the real situation found in our area of study and translated to the second system, copying the share of crops and the net margin per hectare corresponding to the upstream system.

Figure 3 represents a supply-demand equilibrium for a given upstream flows regime (that of the Vadiello Reservoir in an average water year). As we can see, all the water rights are satisfied in the place and time established; that is, there is no deficit for any sector.

On the basis of a situation of equilibrium such as that described above, we can consider two types of problem that might arise as a consequence of changes in the supply and/or demand conditions: first, a situation of drought, assuming a fall in the water supply of 30% (i.e., a fall in upstream inflows); secondly, an increase in the surface area under irrigation of 700 hectares within system 2 (i.e., an increase in the system 2 irrigation needs). In this latter case, the irrigation-based farmers operating within this system wish to have as much surface area under cultivation as their counterparts operating within system 1 (we assume a constant distribution of crops). It should be noted that we are dealing with an optimisation problem based on an annual time horizon.

Figure 3.
Starting point situation



3.2 Specification of the theoretical model

We reduce both problems (drought and increase in downstream requirements) to the same terms: calculate the changes in the operational regime of the hydropower plant that are necessary in order to maximise the joint agriculture-hydropower profit. The resolution of this problem determines certain levels of reservoir-stored water R_{jt} in both periods, various changes in hydropower allotments and, of course, changes in profits for both users.

In order to make the theoretical model operative, a specific profit function is constructed such that m^A_{ij} corresponds to profit per hectare, i.e., the net margin minus other indirect costs, as these are defined in agricultural accounting (e.q. MOPTMA, 1993). As we can see, we assume linear technology. Furthermore, m^H is determined as 8 pesetas/Kwh, the restated value of the margin for hydropower production that appears in the same document. The head is estimated through a function calibrated for the real data of the Vadiello reservoir, $h_j = b \ln(R'_{jt})$, with R'_{jt} being the average reserves in each period. The best fit of the head of the reservoir and the reserves is obtained through a logarithmic function with coefficient 8.2323. Finally, α is the conversion independent of the released flow and head in energy (2180 Kwh/Hm^3).

In system 1, there are 1400 hectares of irrigated area, distributed between four types of crops: cereals, 55%; industrial crops, 29%; vegetables, 15%; and fruit, 1%. In all cases, we assume an irrigation efficiency of 47% (see Bielsa, 1999). In system 2, the number of hectares under irrigation is 700, whilst the distribution of the crops and the irrigation efficiency is assumed to have the same structure as in system 1. Both cases, and their associated reallocations, are described in the following sub-sections.

3.3 Case 1: Reallocation in response to drought

The problem here takes the form of a reduction in the upstream flows of 30%, i.e., a "typical" dry year[4]. Table 1 shows the earlier mentioned changes in the operational regime that are necessary in order to maximise the joint agriculture-hydropower profit, as well as the consequences of these changes in terms of reserves time distribution (R_{jt}). This table contains three blocks for each system: the starting point, the case of drought for current water rights and the distribution of water rights resulting from the maximisation of the joint profit for this new situation (optimum solution).

Table 1.
Fall in water supply of 30% (Drought), Upstream flow of 22.4 Hm^3

System 1	Starting Point		Current Rights		Optimum Solution		System 2	Starting Point		Current Rights		Optimum Solution	
	t=1	t=2	t=1	t=2	t=1	t=2		t=1	t=2	t=1	t=2	t=1	t=2
A_{1t}	**20.0**	**12.0**	**14.0**	**8.4**	**14.0**	**8.4**	A_{2t}	0.0	0.0	0.0	0.0	0.0	0.0
V_{1t}	25.0	27.0	19.0	17.2	19.0	19.4	V_{2t}	14.2	15.8	13.2	11.2	9.7	12.2
$C1_{1t}$	4.0	4.0	4.0	4.0	4.0	4.0	$C2_{2t}$	2.0	2.0	2.0	2.0	2.0	2.0
$C2_{1t}$	4.0	4.0	4.0	4.0	4.0	4.0	$C2_{2t}$	4.0	4.0	4.0	4.0	4.0	4.0
$C3_{1t}$	0.0	12.0	0.0	12.0	0.0	12.0	$C3_{2t}$	0.0	6.0	0.0	6.0	0.0	6.0
$C4_{1t}$	10.0	10.0	10.0	10.0	**8.0**	**14.4**	$C4_{2t}$	10.0	10.0	10.0	10.0	**6.0**	**9.7**
$U1_{1t}$	4.0	4.0	4.0	4.0	4.0	4.0	$U2_{2t}$	2.0	2.0	2.0	2.0	2.0	2.0
$U2_{1t}$	4.0	4.0	4.0	4.0	4.0	4.0	$U2_{2t}$	4.0	4.0	4.0	4.0	4.0	4.0
$U3_{1t}$	0.0	12.0	0.0	4.2	0.0	6.4	$U3_{2t}$	0.0	6.0	0.0	2.7	0.0	3.7
$U4_{1t}$	10.0	10.0	10.0	10.0	8.0	14.4	$U4_{2t}$	10.0	10.0	10.0	8.7	6.0	9.7
Net Demand	10.0	22.0	10.2	12.2	8.0	14.4	*Net Demand*	10.0	12.0	10.0	8.7	6.0	9.7
R_{1t-1}	5.0	15.0	5.0	8.8	5.0	11.0	R_{2t-2}	5.0	4.2	3.8	3.2	2.5	3.7
R_{1t}	15.0	5.0	8.8	5.0	11.0	5.0	R_{2t}	4.2	3.8	3.2	2.5	3.7	2.5
Deficit							*Deficit*						
1Urban	0.0	0.0	0.0	0.0	0.0	0.0	*1Urban*	0.0	0.0	0.0	0.0	0.0	0.0
2Min. flow	-2.0	-2.0	-2.2	0.0	0.0	0.0	*2Min. flow*	-4.0	0.0	-4.0	0.0	0.0	0.0
3Irrigation	0.0	0.0	0.0	**7.8**	0.0	**5.6**	*3Irrigation*	0.0	0.0	0.0	**3.3**	0.0	**2.3**
4Hydropower	0.0	0.0	0.0	0.0	0.0	0.0	*4Hydropower*	0.0	0.0	0.0	**1.3**	4.0	**0.3**
R_1^0	0.0	0.0	0.0	0.0	0.0	0.0	R_1^0	0.0	0.0	0.0	0.0	0.0	0.0
Hydr.Prof*	0.33	0.33	0.28	0.28	0.30	0.30	Hydr.Prof*	0.22	0.20	0.18	0.15	0.16	0.16

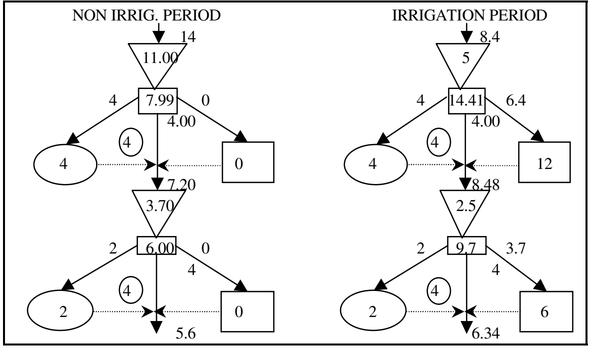
The modified values of the variables and the resulting deficits appear in bold type.
All data in Hm^3 except: Hydr.Prof*: Hydropower profits in pesetas per cubic meter.

Under the assumption of current rights, and following its order of priority, deficits appear in the second period of the dry year. For the hydropower use of system 2, these deficits take the form of the difference between the compulsory withdrawals from the reservoir for the population or for the minimum flow (whichever is the highest) and the releasing demands of that activity. Agriculture only counts on the water left to it by urban requirements and the security stock in the reservoir, with the remaining amount it needs in order to meet its requirements constituting its deficit. As can be noted, the fall in precipitation takes the form of a lower quantity of water stored in the reservoir, a situation that remains throughout the year. Net demand shows the volume of water withdrawn from each reservoir to meet the requirements.

Given that the hydroelectric value of released water depends on the head of the reservoir (and, therefore, on the volume of reservoir reserves), each one of the periods has an associated value of the energy per unit of water used. This value appears in the bottom row of the table.

In the optimum solution, the hydropower plant will change the releasing timetable such that it renounces a part of its initial allotment in the first period. In exchange, hydropower has more water rights in the second period and a higher profit per unit of released water, due to an increase in the level of water stored in the reservoir. In this way, agriculture counts on a larger availability of resources during the irrigation season, which is equivalent to the drought having a lower impact on profits and loss account. The allocation of resources in the optimum solution is presented in Figure 4.

Figure 4.
Optimum Solution



Therefore, if both parties reach an agreement such as that suggested by the optimum solution, an improvement will be achieved in the Pareto sense, as compared to the case in which there is no agreement. This is illustrated in Table 2, which presents the increase in profits from the earlier mentioned change in allotments. Therefore, reallocation of water is expected to generate gains in this case.

Table 2.
Profits in a drought situation under current rights and optimum solution

PROFITS *				
SECTOR	STARTING POINT	CURRENT RIGHTS	OPTIMUM SOLUTION	PROFIT INCREASE
HYDROPOWER	10.86	8.71	9.29	0.58
AGRICULTURE	78.44	30.24	43.93	13.68
JOINT	89.30	38.95	53.21	14.26

* The figures are expressed in millions of pesetas, whilst the profits are the total profits of each sector.

Thus, the figures show that it is possible to establish option agreements related to rainfall conditions (in drought years) between farmers and electricity producers that have the effect of reducing the agricultural losses without diminishing the hydropower profits. These agreements represent a type of drought insurance for agriculture, implying an increase in their effective allocations of water stored in the reservoirs at the beginning of the irrigation season as a result of a reduction in the hydropower allotment in the non irrigation period.

Whilst it would be interesting to study the specific legal form in which this agreement could be reached, this lies beyond the scope of our paper. Here, we only aim illustrating that such an arrangement is, at least on the basis of real data, interesting for both parties.

3.4. Case 2. Reallocation in response to extension in surface area under irrigation

In this case, we assume that there is a plan to double the surface area under irrigation in system 2, while leaving the distribution of crops unchanged. This supposes a permanent deficit of 5.9 Hm^3 for the agricultural sector operating in this system. In fact, it is not possible to meet the additional requirements created by these newly irrigated areas on the basis of the water supply available in an average year, taking into account current hydropower time-distribution allotments.

In such circumstances, we cannot speak of a lack of rainfall, but rather of an increase in requirements that exceeds the possibilities of the current water rights system to satisfy them. Under market conditions this deficit could be met through a relative increase in the price of the good, which is now more scarce. However, given the earlier mentioned institutional structure that operates in Spain, it cannot be expected that such a change will be introduced, at least in the short term.

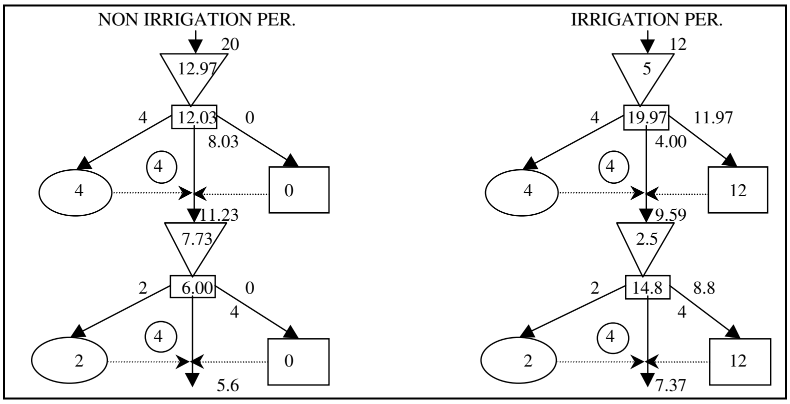
Table 3.
Extension of surface area under irrigation of 700 hectares.

System 1	Starting Point		Current Rights		Optimum Solution		System 2	Starting Point		Current Rights		Optimum Solution	
	t=1	t=2	t=1	t=2	t=1	t=2		t=1	t=2	t=1	t=2	t=1	t=2
A_{1t}	20.0	12.0	20.0	12.0	20.0	12.0	A_{2t}	0.0	0.0	0.0	0.0	0.0	0.0
V_{1t}	25.0	27.0	25.0	26.8	25.0	25.0	V_{2t}	14.2	15.8	13.2	14.6	13.7	17.3
$C1_{1t}$	4.0	4.0	4.0	4.0	4.0	4.0	$C2_{2t}$	2.0	2.0	2.0	2.0	2.0	2.0
$C2_{1t}$	4.0	4.0	4.0	4.0	4.0	4.0	$C2_{2t}$	4.0	4.0	4.0	4.0	4.0	4.0
$C3_{1t}$	0.0	12.0	0.0	12.0	0.0	12.0	$C3_{2t}$	0.0	6.0	**0.0**	**12.0**	**0.0**	**12.0**
$C4_{1t}$	10.0	10.0	10.0	10.0	**12.0**	**20.0**	$C4_{2t}$	10.0	10.0	10.0	10.0	**6.0**	**14.8**
$U1_{1t}$	4.0	4.0	4.0	4.0	4.0	4.0	$U2_{2t}$	2.0	2.0	2.0	2.0	2.0	2.0
$U2_{1t}$	4.0	4.0	4.0	4.0	4.0	4.0	$U2_{2t}$	4.0	4.0	4.0	4.0	4.0	4.0
$U3_{1t}$	0.0	12.0	0.0	12.0	0.0	12.0	$U3_{2t}$	0.0	6.0	0.0	6.1	0.0	8.8
$U4_{1t}$	10.0	10.0	10.0	10.0	12.0	20.0	$U4_{2t}$	10.0	10.0	10.0	10.0	6.0	14.8
Net Demand	10.0	22.0	10.2	21.8	12.0	20.0	*Net Demand*	10.0	12.0	10.0	12.1	6.0	14.8
R_{1t-1}	5.0	15.0	5.0	14.8	5.0	13.0	R_{2t-2}	5.0	4.2	3.8	3.2	2.5	7.7
R_{1t}	15.0	5.0	14.8	5.0	13.0	5.0	R_{2t}	4.2	3.8	3.2	2.5	7.7	2.5
Deficit							*Deficit*						
1Urban	0.0	0.0	0.0	0.0	0.0	0.0	*1Urban*	0.0	0.0	0.0	0.0	0.0	0.0
2Min. flow	-2.0	-2.0	-2.2	-1.8	-4.0	0.0	*2Min. flow*	-4.0	0.0	-4.0	0.0	0.0	0.0
3Irrigation	0.0	0.0	0.0	0.0	0.0	0.0	*3Irrigation*	0.0	0.0	0.0	**5.9**	0.0	**3.2**
4Hydropower	0.0	0.0	0.0	0.0	0.0	0.0	*4Hydropower*	0.0	0.0	0.0	0.0	4.0	-4.8
R_1^0	0.0	0.0	0.0	0.0	0.0	0.0	R_1^0	0.0	0.0	0.0	0.0	0.0	0.0
Hydr.Prof*	0.33	0.33	0.33	0.33	0.32	0.32	Hydr.Prof*	0.22	0.20	0.18	0.15	0.16	0.16

Again, the optimisation exercise shows that it is possible to establish agreements, which will now be of a permanent character, to improve the situation of both users. However, and by contrast to the earlier case, we are now not dealing with two different situations, depending on whether we are referring to a "normal" or to a dry year. Rather, we are considering two possible distributions of the resource over time. The following tables and figures illustrate the three reference scenarios: the starting point situation and the two possible allocations under new agricultural requirements, that is to say, the maintenance of current water rights or reallocation in a optimum solution provided by the maximisation results.

The exchange will take the form of the hydropower plant of system 1 releasing freely (which, under maximisation, will lead to the releasing of 12 Hm^3 in the first period and 20 in the second). For its part, the plant in system 2 will have to renounce 4 Hm^3 of its water rights during the first period in exchange for practically free releasing in the second.

Figure 5.
Optimum solution to extension of surface area under irrigation



In this way, agriculture (both in system 1 and 2) will find itself in a position where practically all the water it requires in the irrigation period will be available from the water stored in the reservoir during the non-irrigation period. The 3.2 Hm^3 of agricultural deficit that remains in the optimum solution for system 2 is independent of the operational regime. In fact, there is simply not enough water to cover all requirements. Once again, the optimum solution shows itself to be superior to that of current rights, given that both users achieve an increase in their profits. These profits and the gain between the two options are illustrated in Table 4.

Table 4.
Profits under current rights and optimum solution with extension of surface area

PROFITS				
SECTOR	STARTING POINT	CURRENT RIGHTS	OPTIMUM SOLUTION	PROFIT INCREASE
HYDROPOWER	10.86	9.94	13.55	3.61
AGRICULTURE	78.44	78.88	90.61	11.74
JOINT	89.30	88.82	104.16	15.34

In summary, the results show that, in the face of a scarcity of resources, negotiating on the distribution of the water rights might not only mitigate the losses resulting from such a scarcity, but could also improve the joint profit of the system. Depending on the case, these negotiations could be transformed into permanent agreements that would suppose a change in the space and time distribution of the resources.

4. CONCLUSIONS

The economic literature contains many examples of how transactions between agents can give rise to efficient allocations and improvements in the Pareto sense. However, allocation of water in Spain has followed procedures very distinct from those recommended by Coase. Thus, in this country water rights are allocated rigidly according to administrative regulations. As a result, exchanges are the exception rather than the rule, and new downstream demands at subsidised prices can be promised by the authorities without taking into account their real upstream effects. Although there are clearly important reasons to question the capability of the market system to efficiently allocate a resource such as water, it is no less true that there are many situations in which the re-allocation of rights could be beneficial for society as a whole.

As a consequence, there is a wide field of study available to us regarding possible exchanges of water rights between one activity and another. In this paper, we are particularly concerned with the possible benefits of these transactions, rather than the legal or institutional form used to bring them about. We would simply remark that, in general terms, any legal reform should be aimed at ensuring that the agents perceive the opportunity cost of the water they are using.

In this context, it is essential to have a correct definition of water rights in all its dimensions, i.e., quantity, quality, spatial location and time. These last two dimensions have sometimes been ignored in the literature and constitute the central focus of our work and its main contribution. Our central objective is to illustrate the form in which both dimensions can be incorporated in the search for optimum allocations. For this reason, we have chosen a situation in which two users (agriculture and hydropower) compete for the water resources of a river in both space and time.

Specifically, we consider what would be the optimum allocation of water between the users when there is a scarcity of the resource. That is to say, we try to determine how water should be allocated in order to increase the profit, or mitigate the losses, derived from that scarcity. This process for the optimisation of the agents' profits (in our case, those of farmers and hydroelectric plants) is conditioned by institutional as well as hydrologic, geographical and time aspects. We construct an optimisation model that incorporates the legal order of priority over the water held by each user and places their requirements in space and time.

The empirical analysis is focused on analysing the requirements (from cities, minimum flow, farmers and hydroelectric plants) associated with two interrelated reservoirs managed in a co-ordinated form. This approach allows us to extend the range of real situations that can be simulated. In this paper we simulate two specific situations of competition for a scarce resource, namely a reduction in streamflow and an increase in irrigation requirements. The results demonstrate the existence of incentives for the hydroelectric plants to review their operational plan in such a way that, at least in some cases, they can assign their rights to agriculture. In these circumstances, we find that making property rights more flexible increases the joint profits of the two types of users.

We believe that an approach of this type would allow us to advance in the necessary integration of the spatial characteristics of water an in economic context. Nevertheless, we clearly cannot forget some important aspects which, although not reflected here, represent natural extensions of this work. Thus, and given the importance of certainty of water supply in the operation of the model, it would be interesting to introduce probability functions of the different levels of upstream flows as well as to obtain the most beneficial allocations in this probabilistic context. Bearing in mind this uncertainty, such allocations would be understood as those which suppose higher profits. Similarly, a consideration of the quality of the water used, both in the definition of property rights and in the allocation process, constitutes a further logical extension of this paper.

NOTES.

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[1] Harpman (1999) or Edwards et al (1999) are two good examples of the treatment of timing in the hydropower operation in the context of environmental constraints.

[2] In Mediterranean climates, the volume of water available (precipitation less plants and crops-transpiration) come fundamentally from the upper reaches of the rivers and are minimal in the mid and lower stretches. That is to say, in our case $A_{2\,t} = 0$. As regards the return flows coming from system 1, note that these correspond both to instream and non-rival uses (minimum flow, whose rate of return flows is 1), as well as to irrigation and urban uses (with rates of return flows of 0.2 and 0.8, respectively).

[3] R and V could be state or flow variables, depending on how we use them. In our approach, we consider their value as a fixed quantity per year and period, no matter how their distribution along the periods are.

[4] Water supply follow a stochastic process that is characterised according to a Normal distribution. The typical dry year will be that which leaves a reduced percentage of the years (for example, 2.5%) "to its left". This means that a guarantee of 100% is not considered as possible in any case, but simply that the risk is delimited to certain lower levels in the absence of this stochastic view.

REFERENCES.

Bielsa, J. (1999): *Gestión del Agua Integrada en el Territorio*". Consejo de Protección de la Naturaleza. DGA.

Zaragoza.

Butcher W.R, Wandschneider P.R. (1986): “Competition Between Irrigation and Hydropower in the Pacific Northwest”, in *Scarce Water and Institutional Change*. K. Frederick, ed. Resources for the Future. Washington D.C.

Chatterjee B., HOWITT R., SEXTON R.J. (1998): The Optimal Joint Provision of Water for Irrigation and Hydropower. Journal of Environmental Economics and Management; 36: 295-313.

Confederación Hidrográfica del Ebro (2000): *Demandas consuntivas y no consuntivas en la cuenca del Ebro*. Confederación Hidrográfica del Ebro.

Coase R. (1960): The Problem of Social Cost. The Journal of Law and Economics; III October: 1-44.

Colby B.G., Randall J.C., Bush D.B. (1993): Water Rights Transactions: Market Values and Price Dispersion. Water Resources Research; 29: 1565-1572.

Dinar A., Wolf A. (1994): “International Markets for Water and the Potential for Regional Cooperation: Economic and Political Perspectives in the Western Middle East”. In *Economic Development and Cultural Change*.

Edwards B.K., Flaim S.J., Howitt R.E (1999): Optimal Provision of Hydroelectric Power Under Environmental and Regulatory Constrains. Land Economics; 75 vol 2: 267-283.

Garrido A. (1994): Mercados de aguas: ¿entelequias economicistas o soluciones a los problemas de asignación?. Revista de Estudios Agro-Sociales;. 167: 89-112.

Gibbons D.C. (1986): *The Economic Value of Water*. Resources for the Future. John Hopkins University Press. Baltimore.

Griffin R.C., Hsu S.H. (1993): The Potential for Water Market Efficiency when Instream Flows Have Value. American Journal of Agricultural Economics; 75: 292-303.

Harpman, D.A. (1999): Assessing the Short-Run Economic Cost of Environmental Constraints on Hydropower Operations at Glen Canyon Dam. Land Economics; 75 vol 3: 390-401.

Howe C.W., Schurmeier D.R., Shaw W.D. (1986): Innovative Approaches to Water Allocation: The Potential for Water Markets. Water Resources Research; Vol 22, 4: 439-445.

Howitt R.E. (1998): “Spot Prices, Option Prices and Water Markets: An Analysis of Emerging Markets in California”. In *Markets for Water-Potential and Performance*. KW Easter, M, Rosegrant and A. Dinar . Kluwer Academic Publishers. New York

Houston J.E., Whittesey N.K. (1986): Modelling Agricultural Water Markets for Hydropower Production in the Pacific Northwest. Western Journal of Agricultural Economics; 11: 221-231.

M.A.P.A. (1999): *Anuario estadístico del Ministerio de Agricultura, Pesca y Alimentación.* Ministerio de Agricultura , Pesca y Alimentación. Madrid.

M.O.P.T.M.A. (1993): *Estudio coste-Beneficio del canal de Itoiz-Navarra.* Ed: Ministerio de Obras Públicas, Transporte y Medio Ambiente

Sumpsi J.M., Garrido A., Blanco M., Varela C., Iglesias E. (1998): *Economía y Política de la Gestión del Agua en la Agricultura*. Mundiprensa and Ministerio de Agricultura, Pesca y Alimentación.

Winpenny, J.T (1994): *Managing Water as an Economic Resource*. Routledge, London.

Young R.A., Haveman R.H. (1985): "Economics of Water Resources: A Survey". In *Handbook of Natural Resource and Energy Economics*, Allen V. Kneese and James L. Sweeney, eds. Elsevier, Amsterdam.