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A cooperative game theory approach to water pricing in a complex water resource system

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Abstract:

The interdisciplinary nature of the planning and management of complex water resources systems requires methods that integrate the technical, economic, environmental, social and legal aspects into a comprehensive framework that allows the development of efficient and sustainable water management strategies.

This research presents a methodology that allocates costs among water users with a cooperative game theory approach based on a fully integrated river basin model with monthly time steps.

The proposed approach starts with the hydrologic and economic characterisation of the system to be modelled. The hydraulic characterisation of the basin includes defining the hydrology with a monthly river-runoff time series, the storage balance in aquifers and reservoirs, and the demand scenario. The economic characterisation of the system is based on the determination of construction costs for new work, the operative, management and replacement (OMR) cost functions definition for hydraulic infrastructures and the shortage penalisation for water use.

Decision support systems tools for water resources systems (AquaTool-SIMGES, Andreu et al., 1996; WARGI, Sechi and Zuddas, 2000) are used to simulate the water system in different configurations, to evaluate the performance and to calculate the characteristic function of each user's coalitions that may be determined in the system. The final cost allocation is calculated using the Shapley Value.

The Turia river basin is considered for a case study. The basin is located in the Valencia and Teruel districts (Spain). The allocation costs problem consists of defining a criterion to distribute the existing system infrastructure costs among users, who then benefit from a supply that meets water demands and flood control.

***Keywords** : Cost allocation, Water Resource Systems, Cooperative Game Theory.*

1. INTRODUCTION

A central problem in planning the provision of public services is how to determine a “fair” and “just” allocation of joint construction work and management costs. This problem is particularly relevant for water systems in Europe to comply with the Water Framework Directive 2000/60, which addresses the recovery costs of water services and adequate contributions from different water uses.

The study of cost-sharing in joint-projects has a long history. The most common approach to the problem has been the normative study of cost-sharing (or surplus-sharing) procedures. Cost-sharing problems can be modelled as cooperative games with transferable utility. The literature provides interesting studies and examples of joint-projects for the cost allocation sharing process in the urban water supply field (i.e., Young and Okada, 1982; Lippai and Heaney, 2000). Cost-sharing solutions, inspired by price systems, have also been studied for airport runways (Littlechild and Thompson, 1977) and power systems (Contreras, 1997), among others. A survey on this matter can be found in Young (1994) with more examples.

Nevertheless, the application of game theory has been mainly restricted to economic or mathematical sciences, which are sometimes far-removed from the complexity and the heterogeneity of engineering problems. The evaluation of the characteristic function is at the base of cooperative games and requires a cost analysis associated with each possible coalition system, which implies an optimisation process whose magnitude grows exponentially with the number of system agents and purposes. Unfortunately, most of the problems related to extended water systems are complex and cannot be optimised using classical procedures. The proposed approach uses the AquaTool-SIMGES (Andreu et al., 1996) simulation and the WARGI (Sechi and Zuddas, 2000) optimisation modules to analyse complex river basins. Hydrologic, hydraulic, economic and environmental aspects, among others, can be taken into account in the system characterisation related to water services. To combine game theory with simulation and optimisation tools, a cost-allocation procedure is proposed to address and solve the pending issues of water pricing in a complex water resource system by means of a sustainable, rational and fair cost-sharing rule. The procedure has been developed to preliminarily identify user needs and to define the set of minimum activities necessary to reach the required service levels; in addition, third party effects and long term externalities are also considered. The outputs of the simulation-optimisation process supply the characteristic function of the game and make it possible to apply a cooperative game-theory algorithm to evaluate cost-allocation.

The methodology is suggested as a tool for decision makers to define water price policies in accordance with the sustainability and fairness principles in the European Water Framework Directive.

2. COST ALLOCATION PROBLEM IN A WATER SYSTEM

In developed countries, water resources are normally considered to be public property whose management represents a natural monopoly. In a natural monopoly, the removal of some services from the free market to avoid duplication of activities and resources is warranted because it is more efficient and convenient than in a free market. Furthermore, once the services quality levels are established, the key factor is the price definition in accordance with the absence of competition and in the context of decreasing average costs (Young R.A., 1996).

The actual water pricing methods are mainly based on the countable or historical cost (sunk costs) allocation corresponding to old investments, and they are used as a simple cost recovery instrument. The cost allocation criterion is generally determined by legal imposition, and the users do not make any decisions, or they are simply consulted about the possible alternatives. The general consent around a certain enforced action is mainly obtained by strong economies of scale or by public subsidies that are able to cut general investment costs.

The Cooperative Game Theory (CGT) approach is particularly appropriate for contexts like water services, in which it is important to define the agreements and to encourage cooperation among decision makers in order to achieve more efficient solutions.

The developed methodology consists of the following main steps:

1. **Water resource system analysis**: definition of the set of management alternatives to reach the service levels required by the users using a simulation model (AquaTool-SIMGES);
2. **Cooperative Game definition**: independent agents’ identification and coalition creation;

3. **Characteristic function calculation**: evaluation of the minimum cost alternative for every coalition using the optimisation model (WARGI);
4. **Game solution**: application of the CGT algorithm.

2.1. Water resource system analysis

The aim of this analysis is to identify basic system service levels and define activities that are necessary to guarantee the water service. The simulation model SIMGES (Andreu et al., 1996) provides a detailed representation of the water system, including a physical characterisation, hydrology, infrastructure definition, demands and water management rules. The basic service levels are calculated with SIMGES, and actions to improve them are also considered. Simulation results include flow and storage evolution at monthly and annual time scales, average values and reliability indexes evaluations.

2.2. Cooperative Game definition

If users are considered independently, the application of N-user game theory requires the evaluation of (2^N-1) coalitions. If each user (*k)* is evaluated for (*p)* purposes, the number of combinations increases to $(2^k-1)(2^p-1)$. A fundamental task in the game definition is identifying the independent agents, which consists of rationally aggregating the users on the basis of common characteristics, such as

- use of infrastructure,
- geographical location,
- service level required (such as reliability criteria, water use priority, water quality, or flood protection),
- demand (monthly and annual consumption),
- demand type (e.g. urban, agricultural or industrial),
- economic activities correlated with water use.

Different users can be grouped into a single player (independent agent) who shares the same expectations and has the same interests. Once the N-players are identified, it is possible to define system coalitions. The agents belonging to a coalition preserve their particular objectives, but in the coalition, they look for the possibility of satisfying them through a common project that saves costs, compared with individual actions. Cost-allocation is addressed in a regulated environment, where the players cooperate to achieve an optimal water service. Agents are motivated to cooperate, by forming coalitions, in order to reduce costs, and they are considered rational, in the sense of persecuting the utility function maximisation.

2.3. Characteristic function calculation

The characteristic function describes the most economical way to provide the required service levels for all the players or coalitions of the cost game. Then, the characteristic function evaluation method is based on the optimisation model WARGI (Sechi and Zuddas, 2000, 2004) that considers, among constraints, the fulfilment of service levels and reliability criteria. The optimal system configuration fulfils the required service level at minimum cost for the predefined coalitions of users.

The coalition definition process corresponds to the criterion traditionally used by river basin authorities to assign new water-use concessions. The lack of third-party influence is possible by defining a “base-scenario” for the system, which represents the system operation without improvements of infrastructure or water services. In the following steps, the activities needed to improve the services are considered, under the condition that users not participating in the project are limited to initial basic service values. In each step, users who are participating in the project within each coalition are defined: these users are called “active players”. Other users are “inactive players”. By using WARGI, it is possible to calculate the optimum cost project for each coalition and to avoid providing benefits to or incurring deficits for third parties. The optimisation process corresponds to a cost-effectiveness criterion because it searches the set of minimum cost activities to achieve a predefined management objective.

2.4. Game Solution

The adopted cost allocation method is the Shapley value (Shapley, 1953), which guarantees an acceptable solution considering the particular characteristics belonging to water resource systems, such as the uncertainty in the final cost of projects, the need to carry out a project in phases, and the existence of “dummy players”. Alternative cost allocation methods are examined in the following case-study.

3. CASE OF STUDY: THE TURIA RIVER BASIN

The Turia river basin is located in the Valencia and Teruel districts and is 6913 km². The system is defined using SIMGES and considers 6 macro-demands, 3 dams, a canal and two pumping systems. For the economic characterisation of the system, previous studies (MIMAM 2000 and 2007, CEDEX 2008) have been considered. Cost functions are related to construction and operational costs; the former are related to infrastructure size and configuration, and the latter are considered as variables that describe water flow. More information about infrastructure costs is provided by Deidda (2009).

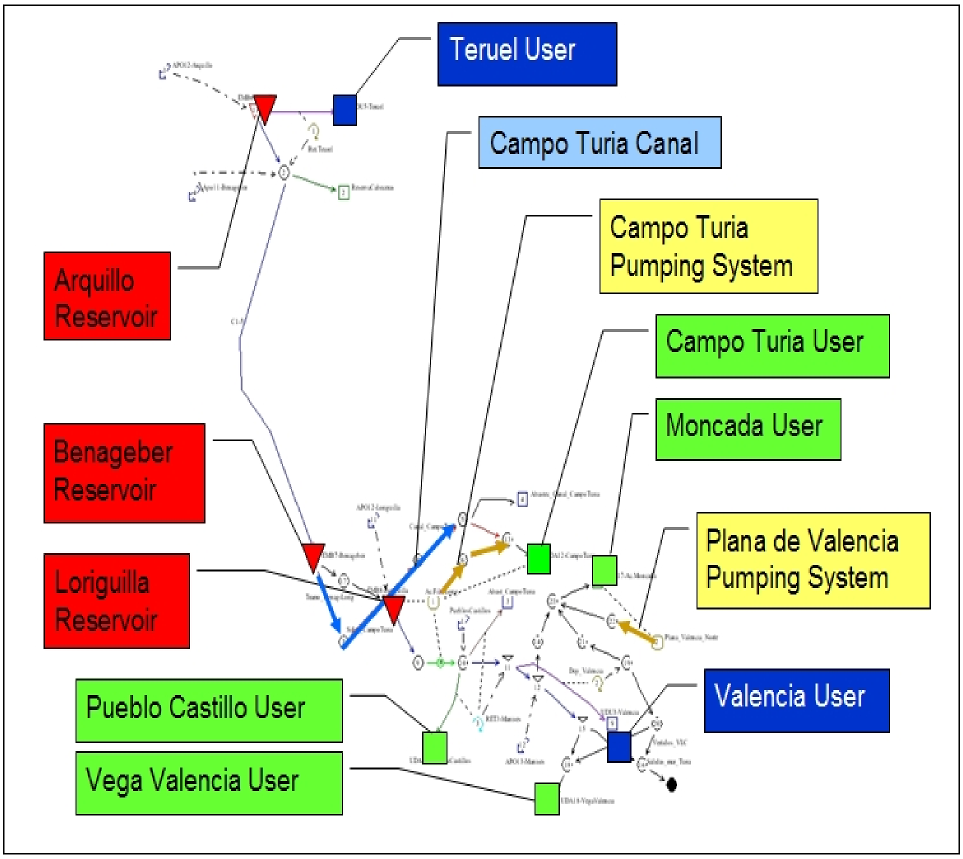

Figure 1. Turia river basin model by SIMGES

3.1. Cost allocation game

The cost allocation game is composed of 4 players:

(A) **Flood control**: represents users requiring flood protection by reservoirs dedicated to flood control;

(B) **Agriculture**: represents demands on the Campo Turia, Acequia de Moncada, Pueblo Castillo and Vega Valencia; the required water resources are given in Table 1;

(C) **Urban**: represents the Teruel and Valencia urban demands, as reported in Table 1. They require high reliability and water quality levels;

(D) **Outside commission user (OCU)**: represents agricultural users who benefit from reservoir regulation without participating in dam management.

Table **1.** Water demands

User	Demand [Mm^3/year]
Teruel	3.17
Valencia	31.53
Pueblos Castillos	51.88
Acequia Moncada	80.85
Campo Turia	85.00
Vega Valencia	80.15
OCU	10.00
Total	342.58

In multi-purpose and multi-users management, we need to minimise system costs by retrieving benefits from scale-economies. The goal of game theory is to allocate costs in such way that no user or group can obtain the same water service at a lower cost, while considering independent activity or activity in combination with different users or users' groups.

3.2. Numerical results

Results obtained by the base-scenario have shown that users are unprotected from water flood damages and that current reliability levels are unacceptable.

Considering the coalitions, we obtain the most efficient infrastructure combination that satisfies the active players' needs. In particular, they are evaluated considering the Spanish Water Authority (MMARM, 2008) guidelines in which the maximum admitted deficit for each demand type is defined (Table **2**).

Table **2.** Maximum admitted deficit

Urban user	
Period	Maximum Admitted Deficit
1 month	10% of monthly provision
10 years	8% of annual provision
Agricultural Users	
Period	Maximum Admitted Deficit
1 year	50% of annual provision
2 years	75% of annual provision
10 years	100% of annual provision

Between cooperative combinations, the grand coalition (ABCD) is constituted by the activities that allow the reliability criteria and flood control objective levels to be met for all the players in a joint form and with minimum cost. In Table 3, the main project data and related construction costs are given. Once the characteristic function of the game is determined and the efficiency of the grand coalition is verified, the allocation cost of the activities is calculated using the Shapley value (1).

$$x_i(c) = \sum_{S \subseteq N-i} \frac{|S|!\left(|N-S|-1\right)!}{|N|!}\left[c(S+i)-c(S)\right] \qquad (1)$$

where:

$x_i(c)$: assigned cost to player i,

|S|: cardinality of coalition S,

|N|: cardinality of grand coalition, (players involved in the game),

c(S+*i*): cost function of coalition (S+*i*),

c(S): cost function of coalition S.

Table **3.** Grand coalition project

Grand coalition (ABCD)					
	Arquillo Reservoir	Benagéber Reservoir	Loriguilla Reservoir	Pumping System	Canal
Project data	Mm³			Mm³/month	
	4.69	221.49	24.46	8.30	10.07
Costs (M€)	2.32	35.52	6.95	37.32	7.15
Total (M€)	89.26				

Table **4** shows the allocation costs for the players using the Shapley value. The greatest contribution is from agriculture because of the high quantity of consumed resource. Furthermore, the agricultural community must use irrigation, in addition to groundwater, which increases water service costs. Another factor is the exclusively agricultural use of canal Campo Turia, which contributes to the increase in the differential cost between agriculture use and other uses.

Table **4.** Allocation costs using the Shapley value

Shapley value		
A	10.28 M€	11.52%
B	76.41 M€	85.61%
C	2.10 M€	2.35%
D	0.47 M€	0.52%
Total	89.26 M€	100%

3.3. Comparison of methods

We can also compare the cost allocations by using different methods. Assuming that all players participate in a joint project with a total cost of 89.26 M€, we also consider proportional allocation of total costs;

separable costs with proportional allocation of no separable costs; proportional allocation of cost savings.

All the methods fulfil the efficiency condition, as they are associated with the most efficient solution and the principle of cost recovery. Nevertheless, only the Shapley value represents a core solution, as defined by CGT, because it fulfils the rationality and marginality principle. It is confirmed in Table **5** where a comparison among the different methods is presented: more/fewer highlighted cells represent an upper/lower allocation compared to the core boundary.

Table **5.** Comparison of allocation costs using different methods

S	Core boundary		Shapley	Proportional costs	Separable costs	Cost savings
	x(S) >	x(S) <				
A	3.90	17.30	10.28	17.85	6.73	13.99
B	69.61	83.82	76.41	63.15	79.63	72.11
C	1.15	3.70	2.10	6.33	2.15	2.52
D	0.44	0.99	0.47	1.92	0.75	0.63
AB	85.20	88.08	86.69	81.00	86.36	86.10
AC	4.95	19.62	12.38	24.19	8.88	16.52
AD	4.28	17.33	10.75	19.77	7.48	14.62
BC	71.93	84.98	78.51	69.49	81.78	74.63
BD	69.64	84.31	76.88	65.07	80.37	72.74
CD	1.18	4.06	2.57	8.25	2.90	3.16
ABC	88.27	88.81	88.79	86.69	86.69	86.69
ABD	85.56	88.11	87.16	82.92	87.10	86.73
ACD	5.44	19.65	12.85	26.11	9.63	17.15
BCD	71.96	85.36	78.98	71.41	82.53	75.27
ABCD	0.00	89.26	89.26	89.26	89.26	89.26

3.4. Core and cost allocation

Figure shows the graphical representation of the cost allocation for the case study. The tetrahedron of feasible solutions and the inside core space is represented. Note that the core is positioned toward the B-vertex, corresponding to the agricultural uses, and the Shapley value is a core solution.

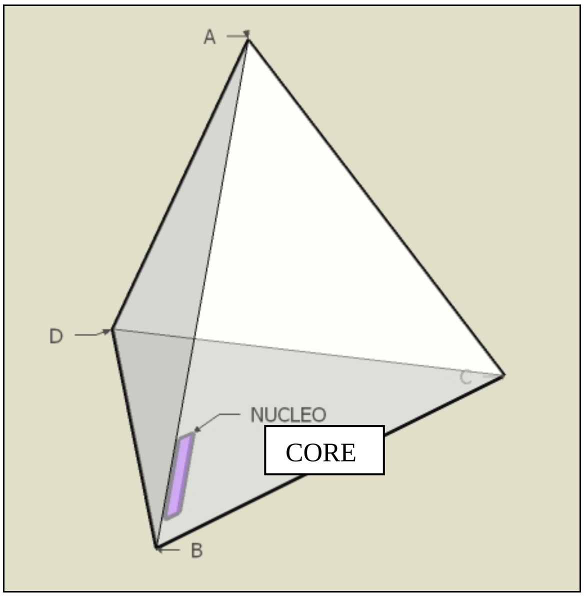

Figure 2: Core solution

4. SUMMARY AND CONCLUSIONS

The paper presents a method based on the application of cooperative game-theory using the support of simulation and optimisation tools. The cost allocation problem is addressed as an infrastructure cost game, in which the players act individually or in coalition in order to obtain an acceptable water service level at minimum cost. Simulation and optimisation tools are used to analyse the water system and to obtain the cost function by selecting the optimal set of infrastructures for each coalition. Once the cost function is calculated, we proceed to allocate total costs by means of the Shapley value.

In the numerical example of the Turia River we calculate the cost allocation of infrastructures for water regulation and flood control services among the users, including urban and agricultural water supplies and acceptable population protection against floods. The obtained cost function is used to determine the core of the cost game. The proposed method can be considered to be a valid instrument for defining the negotiation phase and identifying the best solution, according to rational, sustainable and equitable principles. The Shapley value seems to be a good compromise in the evaluation of cost allocation for this problem because it provided an efficient solution even in a situation with a narrow core, where other methods can fail. Allocating the water service costs among users shows that a great part of the costs are attributed to agricultural uses, which are higher water consumers, the water supply of which is obtained in part by pumping groundwater. The analysis of the results shows the existence of economies of scale that are mainly related to the multiple uses of reservoirs for flow regulation and flood control.

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