WPS4074

COOPERATIVE GAME THEORY AND ITS APPLICATION TO NATURAL, ENVIRONMENTAL AND WATER RESOURCE ISSUES:

3. Application to Water Resources

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Abstract

This paper provides a review of various applications of cooperative game theory (CGT) to issues of water resources. With an increase in the competition over various water resources, the incidents of disputes have been in the center of allocation agreements. The paper reviews the cases of various water uses, such as multi-objective water projects, irrigation, groundwater, hydropower, urban water supply, wastewater, and transboundary water disputes. In addition to providing examples of cooperative solutions to allocation problems, the conclusion from this review suggests that cooperation over scarce water resources is possible under a variety of physical conditions and institutional arrangements. In particular, the various approaches for cost sharing and for allocation of physical water infrastructure and flow can serve as a basis for stable and efficient agreement, such that long-term investments in water projects are profitable and sustainable. The latter point is especially important, given recent developments in water policy in various countries and regional institutions such as the European Union (Water Framework Directive), calling for full cost recovery of investments and operation and maintenance in water projects. The CGT approaches discussed and demonstrated in this paper can provide a solid basis for finding possible and stable cost sharing arrangements.

World Bank Policy Research Working Paper 4074, November 2006

This Working paper is a product of the first phase of the study “Cooperative Arrangements for Allocation of Water among Production and Environmental Uses under Stochastic Supply Conditions”, funded by the Italian Trust Fund and the Development Economics Research Group of the World Bank. Members of the study team include: Ariel Dinar (Task Manager), Fioravante Patrone, Irene Parrachino, Stefano Zara of the University of Genoa, Carlo Carraro, Carmen Marchiori, and Alessandra Sgobbi of the University of Venice. Comments by Rashid Sumaila, University of British Columbia, Canada and Kim Hang Pham Do, Massey University, New Zealand, and participants of the 6th meeting on Game Theory and Practice Dedicated to Development, Natural Resources and the Environment, July 10-12, Zaragoza, Spain, are much appreciated. Two additional Working Papers are also devoted to some special topics, which are chosen having in mind their use in applications to environmental issues: 1. Basic Thoery (PRWP 4072), and 2. Application to Natural and Environmental Resources (PRWP 4073).

CONTENTS

INTRODUCTION

Many economic activities have been subject to strategic behavior on the part of individuals or firms (from hereafter—players or parties), especially when the groups involved are not too big. Game theory has been providing important input to policy making in several sectors (e.g., communication, transportation, aviation, energy). In the specific field of water resources, game theory has not been used to its full capacity by social science experts and practitioners.[1] While in other fields non-cooperative behavior is common, we see much more focus on cooperation in the field of water. What makes water more appropriate for cooperation among the parties involved? First, significant economies of scale make it more attractive to build bigger rather than smaller water projects, thus, there is an incentive for inclusion; and second, the level of negative externalities associated with water utilization is a big incentive to cooperate and reduce such impacts.

Most of the cooperative game theory (CGT) applications are about sharing benefits. Benefits can be created both from saving on investment and operational cost and from increasing welfare that is associated with the utilization of the resource—e.g., new opportunities that are not available when no cooperation is considered. What CGT offers in most cases is an allocation of the benefits from cooperation that, depending on the solution (allocation scheme) concept, fulfill certain requirements.

The paper will review a set of works that have been identified in the literature that include applications to allocations resulting from cooperation in dams, water supply and wastewater treatment facilities, water exchange (water markets and water rights), groundwater, multipurpose water facilities, and transboundary water conflicts. The list of CGT solution concepts will include: The Core, The Shapley Value; The Nucleolus; The Generalized Shapley; Nash/Nash-Harsany; and others. We will also refer to some non CGT allocation solutions, such as Egalitarian Non-Separable Cost (ENSC); Alternate Cost Avoided (ACA); Separable Costs Remaining Benefits (SCRB); Marginal cost; and Proportional use. All the non CGT allocation solutions have been applied in certain works and will be used for comparison purposes.

For the purpose of organization of the paper, we grouped the reviewed works by the sub-sectors to which they have been applied. This structure allows us to provide sub-sector specific focus, but this also comes at the expense of extrapolating among features of the sub-sectors that could be relevant to other sectors. To fix this drawback, we added at the end of the paper a section that cross cuts among the sub-sectors and attempts at deriving general lessons and recommendations.

THE CASE OF MULTIPURPOSE WATER RESOURCE PROJECTS

The Tennessee Valley Authority (TVA) case is probably both the earliest and the richest case that offered game theorists an opportunity to examine, from a CGT point of view, a practical problem of cost allocation in a water resources development project among various components that have been designed as part of that project. Ransmeier, (1942) provides an authentic description of the TVA project, and especially on the various attempts to allocate, using non CGT schemes, project costs among various project components. Following Ransmeier, (1942), we find several attempts to apply CGT concepts to the TVA case.

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[1] This is a third in a series of three working papers on cooperative game theory principles and their application to natural, environmental and water resources. The first paper “COOPERATIVE GAME THEORY AND ITS APPLICATION TO NATURAL, ENVIRONMENTAL AND WATER RESOURCE ISSUES: 1. Basic Theory” by Irene Parrachino, Stefano Zara and Fioravante Patrone. The second paper “COOPERATIVE GAME THEORY AND ITS APPLICATION TO NATURAL, ENVIRONMENTAL AND WATER RESOURCE ISSUES: 2. Application to Natural and Environmental Resources” by Stefano Zara, Ariel Dinar and Fioravante Patrone.

In a following paper, Parker, (1943) focuses on the various theories applicable to the allocation of costs of a multiple-purpose water control project, and presents the procedure followed by the TVA in allocating the cost of its first three dams to navigation, flood control and power. It is shown that a large difference in the allocation of the common costs of a project affects to a much lesser degree the proportion of the total cost charged to the individual purposes. Consequently the final allocations are approximately correct, within reasonable limits, regardless of the exact methods adopted.

We report only the main methods because they capture implicit GT principles. (To remind ourselves, the analysis is about the cost allocation for the first three dams built for navigation, flood control and electric power production.)

The analysis of the TVA cost allocation (Ransmeier, 1942) distinguished between *direct costs* (due to a particular sector of the multipurpose project) and the *remaining joint costs*. Although no cost sharing rule was specifically chosen the *Egalitarian*, the *Alternate Cost Avoided* (ACA) method and the *Alternative Justifiable Expenditure* method most influenced the final allocation. A modification of the ACA method, called the *Separable Cost Remaining Benefits* (SCRB) method gained acceptance during the 1940s and the Federal Inter-Agency River Basin Committee (1950) recommended its utilization for the allocation of costs in a joint water facility project.

The rules used indicate that “Expenditures made solely for a single purpose are to be charges directly to that purpose. The following methods of allocation were considered by the committee” (Parker 1943): *Vendibility Theory* (but there isn’t a market where the facilities dealt with can be sold), *Benefit Theory* (but there are difficulties in estimating the benefits derived from the project), *Use of Facilities Theory* (that is, a method allocating costs upon the basis of comparative use of the common facilities, but it is too difficult to estimate comparative use due to lack of data), *Equal Apportionment* (“common-sense rule of equity to be used when it is felt that no truly scientific basis of apportionment can be found. However such a rule does not seem practicable where the respective uses for each function are not equal”), *Special Costs* (apportionment of the cost proportional to the special expenditures for each use, but it can also be used for the joint costs), *Alternative Justifiable Expenditure* (the joint costs can be divided in proportion to the alternative justifiable expenditure minus the direct cost for each function, where for *direct cost* we mean the marginal contribution to the joint cost of a project and the *alternative justifiable expenditure* is the lowest cost, justified by the benefits obtainable, of realizing the project outside the joint facility to get the same benefits). The author concludes that “There is no real justification for basing the allocation … upon any one mathematical formula”. In the meantime the evolution of Cooperative Game Theory provided many new tools for the analysis of that kind of problems, from the *Imputation Set* and the *Core* concepts, anticipated by some TVA criteria in Ransmeier (1942), to more “sophisticated” solution concepts.

Straffin and Heaney (1981), made the first relevant contribution to this literature. They outlined some basic CGT principles embedded in the TVA analysis and “translated into GT language” the main cost apportioning methods. Driessen (1988) applies several CGT cost allocation methods to the case of the TVA, comparing the τ-value, the Nucleolus, and the Shapley value, and similarly to Tijs and Driessen (1986) demonstrates, using some theorems, that for certain subclasses of games the τ-value coincides with the ENSC and with the SCRB methods. In a similar way, Young (1994a, 1994b) proposes the TVA also as a rich example for a range of issues and cost allocation methods.

Straffin and Heaney (1981) applied solution concepts, including the core, a special case of the nucleolus, and the imputation which minimizes the maximum propensity to disrupt. A method equivalent to the latter, but with a different rationale, is now in standard use among water resource professionals.

The authors describe the TVA multipurpose problem, in a CGT model, as follows. N is the set of n purposes among which costs have to be allocated, $C(S)$ is the cost function for each subset S of N ($S \subset N$), and thus $C(N)$ is the total cost and $C(i)$ is the cost of a single project.

A *cost-allocation* is a vector:

$$\left(c_1,...,c_n\right), \text{ such that } \sum\nolimits_{i=1}^{n} c_i = C\left(N\right) \text{ and } c_i \geq 0$$

The "preliminary criterion of a satisfactory allocation" originally listed by Ransmeier (1942) in his presentation of the problem corresponds to the *Core* of this cost game:

$$c_i \leq C_i \text{ and } \sum_{i \in S} c_i \leq C\left(S\right) \text{ for all } S \subseteq N$$

If we consider the *savings-game* (N, v) corresponding to this cost-game, we will have:

$$v\left(S\right) = \sum_{i \in S} C\left(i\right) - C\left(S\right)$$

These savings can be obtained by the subset S of projects.

We have:

$v\left(i\right)=0$ and $v\left(S \cup T\right) \geq v\left(S\right)+v\left(T\right)$ in the TVA case study. This is equivalent to say that v is *zero-normalized* and *superadditive*.

The allocation to be chosen will now be a *vector of savings*: $\left(x_1,...,x_n\right)$ where:

$$x_i = C\left(i\right) - c_i$$

and, if we look for an imputation lying in the Core, it must be:

$$\sum_{i=1}^{n} x_i = v\left(N\right), \;\; x_i \geq 0 \text{ and } \sum_{i \in S} x_i \geq v\left(S\right)$$

for all $S \subseteq N$.

The Core of the TVA game is non-empty (the game is convex), but it consists of a set of infinite points, thus there is the problem of choosing between them.

Almost all the methods considered by the TVA charge each purpose a minimum cost called *separable cost*, that is, the change in the cost of a multipurpose project due to adding a project to the set of the others:

$$SC_i = C\left(N\right) - C\left(N - \{i\}\right)$$

If the savings game is convex it follows that:

$$SC = \sum_{i=1}^{n} SC_i \leq C\left(N\right)$$

and the allocation problem turns to be the allocation of the *non-separable costs*:

$$NSC = C\left(N\right) - SC$$

A possibility is the *equal allocation* of the *NSC* among the projects:

$$c_i = SC_i + \frac{NSC}{n}$$

In terms of the savings-game,

$$x_i = C(i) - c_i = v(N) - v(N-\{i\}) - \frac{1}{n}\left[\sum_{j=1}^{n}\left(v(n) - v(N-\{j\})\right) - v(N)\right]$$

The authors propose three numerical examples (three-person games) to show that the vector $E = (x_1, ..., x_n)$ (obtained as explained above), can be an *imputation* or not, can be in the *Core* or not, and can even coincide with the *Nucleolus*, depending on the game.

Another method proposed by a TVA consultant, Martin Glaeser, in 1938, assigns to each project this charge:

$$c_i = SC_i + \frac{C_i - SC_i}{\sum_{j=1}^{n} C(j) - SC_j}$$

This method attributes to a project its separable cost and a rate of the *NSC* proportional to $C_i - SC_i$. This difference is the *Alternate Cost Avoided*.

In 1974 Gately proposed a new solution concept for *n*-person cooperative games defining player *i*'s *Propensity to Disrupt* an imputation:

$$d_i = \frac{v(N) - v(N-\{i\})}{x_i} - 1$$

This quantity represents the ratio of what the members of coalition *N* - *i* would loose if player *i* disrupted the grand coalition, to what player *i* himself would lose. Gately's apportionment method, based on minimizing the maximum propensity to disrupt, is exactly the TVA *ACA method*.

The final TVA cost allocation was "not based exactly on any one mathematical calculation or formula, the final sums being fixed by judgment and not by computation" (Parker, 1943). However the ACA method was the principal method used to guide that judgment, and a modification of this method is the allocation method which has gained widest acceptance among water resource engineers and is still in use.

In this modification $C(i)$ is replaced by min [$B(i)$, $C(i)$]:

$$c_i = SC_i + \frac{\min\left[B(i) - C(i)\right] - SC_i}{\sum_{j=1}^{n} \min\left[B(j) - C(j)\right] - SC_j}$$

This is called Separable Cost Remaining Benefits method.

The authors conclude: "No single allocation method, or no simple game theoretic solution concept, can claim to be uniquely "best". In this domain, rationality seems to demand a multiplicity of viewpoints, and narrow insistence on the virtues of one method is a vice rather than a virtue."

In the following papers the subset solution concepts are used as a guideline, and the one-point solutions are compared and discussed in order to choose an allocation, whenever the Core boundaries leave the possibility of such a choice, that is whenever the Core is nonempty. In the literature about multipurpose water project the CGT framework always consists an *n*-person cooperative game with side payments, and the cost-sharing rules that we found applied in the literature are: the ENSC, ACA, SCRB, MCRS methods, the Shapley value, the Nucleolus, and the τ-value (NSCG method). Most of the papers compare numerical outcomes derived from the different allocation rules, and some authors enter to the equity and fairness fields also, requiring some properties for a cost allocation rule.

In a paper that focuses on efficiency and equity criteria of cost allocation methods in water projects, Loughlin (1977) analyzes the *SCRB method*, which assigns to each purpose the separable cost of including it in the multipurpose project, plus a share of the joint costs, and the *Alternative Justifiable Expenditure method*, which substitutes the specific costs of the various functions to their separable costs.

Loughlin refers to three *efficiency* conditions: “(1) The separable cost of adding each purpose as the least increment should not exceed the benefits deriving there from, (2) the sum of the total costs allocated to each purpose should not exceed the sum of the total benefits allocated to each purpose, and (3) the total costs allocated to each purpose should not exceed the cost of a single-purpose alternative providing equivalent benefits.” These three efficiency criteria are satisfied by the SCRB method.

Equity of a cost allocation refers to fairness in the distribution of total project costs among all the purposes served by a multi-purpose development. Specifically, an equitable cost allocation is one which permits all project purposes to share in a fair way the savings from multi-purpose rather than single-purpose construction.

On efficiency grounds, only the SCRB formula satisfied all three efficiency criteria. From an equity viewpoint, no one method allocates costs so that each purpose shares fairly in the savings from multiple-purpose development. The source of inequity with the SCRB and alternative justifiable expenditure methods arises because either separable costs or specific costs are subtracted from the justifiable costs on a 1:1 basis. Conceptual problems in defining capacity preclude the use of facilities methods from satisfying the equity objective. An adjustment in the SCRB method is proposed which will enable this procedure to satisfy both efficiency and equity criteria.

The author introduces an *“adjusted” SCRB method*, to avoid inequity: he proposes to “apply a credit to the separable costs so that separable costs are subtracted from justifiable costs on a grater than 1:1 basis. The credit could be in the same ratio as that of the justifiable costs for a purpose plus justifiable costs for all other purposes to the total project costs. This procedure would provide better results than the existing SCRB method for meeting the equity criterion. (…) The effect of this change would be a tendency for the savings allocated to each purpose to bear a more proportionate relationship to the savings from inclusion of each purpose in the project.”

Dickinson and Heaney (1982) suggest an alternative allocation method, the minimum costs, remaining savings (MCRS), as a generalization of the presently used separable costs, remaining benefits method. The purpose of the paper is to address some *fairness* criteria corresponding to the *Core* of an *n*-person TU-game. These criteria reduce the set of admissible solutions, but additional criteria are required to get a unique solution. The method is introduced by a numerical example, and later formalized.

It is shown that the SCRB method works fine if the Core is nonempty: in the case of an empty Core the SCRB leads to a “not very reasonable compromise solution”. A way to find a compromise solution is to relax some Core bounds until a Core appears and one way is to relax the bounds on the intermediate coalitions *S*.

A linear program problem can be formulated:

$$\min \theta, \quad \text{subject to:}$$

$$x(i) \leq c(i) \quad \forall i \in N$$

$$\sum_{i \in S} x(i) - \theta c(S) \leq c(S) \quad \forall S \subset N$$

$$\sum_{i \in N} x_i = c(N), \quad x(i) \geq 0$$

The meaning of these equations is, in the case of an empty Core, to find the minimum value θ which yields a nonempty Core: the new bounds will provide a point Core. In the authors' opinion this method is "a more general procedure for allocating costs which is felt to be theoretically sound, computationally simple and easy to relate to existing practice".

Driessen and Tijs (1986) compare four different allocation methods, which allocate the joint costs of water resource projects among its participants on the basis of separable and nonseparable costs: the egalitarian nonseparable cost (ENSC) method, the separable cost remaining benefits (SCRB) method, the minimum cost remaining savings method, and a new method, the so-called nonseparable cost gap method, which is derived from the τ-value, a game theoretical concept (Tijs, 1981).

In the SCRB method the separable cost is attributed to each player, and the allocation of the remaining non-separable costs is based on the alternate cost of the one-person coalition. However there is no reason why the remaining alternate costs of other coalitions should not be taken into account in the allocation of the non separable cost.

The authors introduce the *cost gap function* g^c, assigning to any coalition *S* the remaining alternate cost of *S* given by:

$$g^c(S) = c(S) - \sum_{j \in S} SC_j(c)$$

Note that:

$$g^c(N) = N \cdot SC$$

Let $g^c(\varnothing) = 0$.

In general, for the games dealing with multipurpose situations we have:

$$g^c(S) \geq 0 \quad \forall S \subseteq N.$$

If we consider a player $i \in T$, we can imagine that the player will reject an allocation that charges him more than $SC_i + g^c(T)$: here the other players in the coalition T are charged only by their SC, while player *i* is charged the remaining cost (worst situation for *i*). This is true for each coalition he belongs to, thus he won't be paying more than

$$\min_{T:i \in T}\left[SC_i(c) + g^c(T)\right] = SC_i(c) + \min_{T:i \in T} g^c(T)$$

If we define the *concession amount* for player *I* as

$$\lambda_i(c) = \min_{T:i \in T} g^c(T)$$

then the non separable cost gap method allocates the NS costs among the players proportionally to λ_i. (If the one-person coalitions determine the minimum gap, then the NSCG method coincides with the SCRB.)

Without entering into details the authors note that the Cost Gap method has "nice" properties such as efficiency, individual rationality, symmetry, continuity, the dummy player property, the dummy out property, the strategic equivalence property and the complementar monotonicity.

The application of this method was demonstrated by Young et al. (1982), using the three neighboring municipalities dealing with a water supply problem.

After this description of the *Non Separable Cost Gap (NSCG) method*, it is compared to the SCRB method (the two allocations coincide if the cost game is semi-convex) and to the MCRS method. For convex cost games the three rules use the same bounds for the Core and consequently their outcomes coincide, but there is no guarantee for these allocations to be inside the Core of the game.

The NSCG is also compared with the ENSC. This allocation rule, which divides the non-separable costs equally among the players/sectors, should be preferred in a special subclass of games called *one-convex cost games*. For these games, in fact, the resulting cost allocation lies in the centre of gravity of the Core. In this situation the ENSC coincide with the SCCG and MCRS methods, but does not with the SCRB.

In a separate attempt, Owen (1993) provides two characterizations of the alternate cost avoided method, one on a class of cost games with a fixed player set, and the other on a class of cost games with a variable player earlier two of the methods examined by the TVA in the 30's, while facing their cost allocation problem for the multipurpose water resource project, were the *Egalitarian Non-Separable Cost* (*ENSC*) method, and the *Alternate Cost Avoided* (*ACA*) method. A modification of the ACA method is the *Separable Cost Remaining Benefit* (*SCRB*) *method*.

A game theoretical basis for the ACA method was first proposed by Gately (1974), with his new concept of players' "*propensity to disrupt*" a coalition. Owen (1993), after an overview in a GT framework of some of the TVA cost allocation methods, provides an axiomatic characterization of the ACA method for a certain class of cost games with a fixed player set (CG^N), and for a class with a variable player set, using a reduced game property. The author demonstrates through a theorem, in a similar way to the characterization of the τ-value given by Tijs (1987), that the ACA method is the unique cost allocation method satisfying *invariance w. r. t.*, *strategic equivalence* and *weak proportionality* properties.

In a recent paper, Serghini (2003) Introduces the FDC (Fully Distributed Costs) allocation rules, and applies it with the Shapley value and the Nucleolus to multipurpose dam projects in Morocco. More than the half of dams in Morocco are multipurpose (hydroelectric power, irrigation, urban supply and, sometimes flood prevention). The entire infrastructure is owned by the ministry of public works, which manages also the dams. The irrigation and urban water supply facilities are managed by the ministry of rural development and water. As can be imagined, disputes over timing and tariffs are common. The author describes two methods for apportioning the costs: the *Fully Distributed Costs* (FDC) methods, assigning the cost of the service plus a fraction of the joint costs and the main apportioning methods based on applied and interpreted in a CGT framework modeling for a multipurpose water resource project.

A case study (the Dchar El Oued dam for hydroelectric power, irrigation, urban and industrial supply) is analyzed. The author explains the allocation mechanism that has been chosen for the cost of the dam. According to the World Bank report (1995) concerning the water sector in Morocco, the urban fees have to cover all the costs, including those due to mobilizations. This will imply an increased cost charged to the users. Choosing a cost allocation method in a multipurpose project is not easy, but it allows the application of an acceptable and equitable method for all the users. Serghini underlines that the choice of a rule has different consequences on "small" and "large" users: for example the "small" services take advantage of non separable cost allocation proportional to the rate of consumption and Nucleolus, while the "large" ones "prefer" the Shapley value, the ACA and the SCRB methods. Among the ten methods applied to the project, the Shapley value seemed to be the most suitable.

URBAN WATER SUPPLY

The following two papers deal with three distinct cost allocation steps for an urban water supply system. The problem consists of three steps, namely (1) aggregating the players into groups to keep the problem manageable; (2) finding an allocation among the players in each group; and (3) finding an allocation scheme for each type of use (e.g., large homes, small homes) within each municipality.

Hashimoto et al. (1982) using a case from Sweden, demonstrate two of these steps. Eighteen Swedish municipalities wishing to develop an urban water supply system are divided into 6 groups, each considered as single agents; the second step is only mentioned in that paper, and it consists of a cost allocation among the single municipalities within each group. The third step is demonstrated by Lippai and Heaney (2000), and concerns urban fees for different kinds of users. The peculiar aspect in these applications of CGT to water supply systems is just the presence of 'natural' groups considered as single agents in the models.

At the highest level (groups of municipalities), the cities are naturally bent together because of logistical considerations (geography, hydrology, existing networks…), at the lowest (single-family users) the charges are drown for different categories of users on the basis of the quantity and quality measures of water consumption.

Hashimoto et al. (1982) address the notion of 'fairness' within the comparison of the 'classical' allocation methods to the CGT ones: fairness in this case is associated with the concept of the *Core* of a *TU-game* (individual rationality, group rationality, efficiency). The authors' conclusion is that even if CGT methods need more information and data, they are less arbitrary than the non-CGT ones, and thus they can be more suitable: for example in the *SCRB method* the boundaries between direct and indirect costs are not so well defined. The application of 'classical' cost apportioning methods does not guarantee individual and group rationality, while for CGT methods some problems may arise because of the non-monotonicity of many solution concepts.

The authors' analysis consists of two parts. First, they discuss certain established principles of 'fairness' through which the different methods can be judged. Then, they compare the solutions given by each method in the case study. The focus is on the behavior of these apportioning methods in practice, rather than on a strict and theoretical axiomatic characterization. The CGT concepts applied are the *Core*, the *Least Core*, the *Nucleolus*, the *weak Least core* and the *weak Nucleolus*, the *proportional Least Core* and the *proportional Nucleolus*, and they are compared with some 'classical' apportioning methods, such as the *SCRB method* and other methods allocating costs in proportion to some single numerical criterion (e.g. use, population, benefit etc.).

While defining the cost function, the first problem in this case study was to identify the independent actors in the system: 18 municipalities were involved, but only some of the possible $2^{18}-1$ groupings being realistic. Some 'natural' groups could be identified, on the basis of past associations, geographical location, existing water supply network and hydrological and geographical features: the cities have been consequently grouped into six independent units, according to these considerations.

The apportionment of costs can be done in two steps: at first among the six groups and later among the single municipalities. (Note that considering the single municipalities since the beginning might not give the same results.)

Some uncertainties in the definition of the cost function arise, since "the definition of the cost function is always somewhat arbitrary in practice".

Using the developed cost function, the cost allocations given by the different methods described in the previous section are compared. The results of the proportional allocation methods (proportional to water demand and to population) and those given by the SCRB don't satisfy the requirement of individual rationality and/or group rationality. Furthermore, "in practice the borderline between direct and indirect costs is not always clear".

In the numerical comparison of the different outputs, the authors note "the 'proportional' allocations differ markedly from the others".

“Since group rationality and marginal cost coverage seem to be essential from the standpoint of equity, that is, to provide sufficient incentives for cooperation, the remaining three methods, the nucleolus, the weak nucleolus, and proportional nucleolus, are potentially more desirable than those discussed above, as they always produce a Core imputation if one exists.”

A method should also be adaptable to changing conditions (since Ransmeier, 1942), that is, for example, if total costs increase then no participant should be charged less. This property is called monotonicity and several of the methods considered do not satisfy it. This may cause problems because total project costs are not well defined until the project is completed, and the first agreement will be based on an estimate: thus it becomes fundamental for the method to ‘follow the changes’ in a reasonable way. ‘Proportional’ methods are obviously monotonic, and the same holds for the *Shapley value*, the *weak* and the *proportional Least Core*, the *weak* and the *proportional Nucleolus*.

Among the ‘classical’ methods the proportional one is considered preferable by the authors, while among the CGT ones the proportional Nucleolus seems to be the best: first of all it is monotonic, second the authors believe that perhaps “A reasonable scheme would be to divide any unforeseen costs in proportion to the benefits enjoyed. This is precisely the way in which the proportional Nucleolus work.”

Appendix A, at the end of their paper carefully describes the procedure used to determine the capital costs of pipes and pumps necessary to supply the demand of water; Appendix B demonstrates that some of the methods satisfy the monotonicity property.

A similar assessment is made by Lippai and Heaney (2000) where CGT allocation solutions are considered more useful than the ‘classical’ ones in getting fair charges for the users. The purpose of their paper was to present a method for the determination of efficient and equitable impact fees for urban water systems for each user, based on the type of demand on the system. The paper deals with the importance of assuring a fair assessment of impact fees for an urban water supply system: the cost of the project needs to be equitably allocated among all existing and new users.

Nelson (1995) described various ways to determine System Development Charges (SDCs) for water, wastewater, and stormwater systems: Market Capacity method, Prototyp System method, Growth-related Cost Allocation method, Recoupment Value method, Replacement Cost method, Marginal Cost method, Average Cost method, Total Cost Attribution method. Applying these methods to a case study Nelson showed that the deriving charges are distributes on a wide range. None of the mentioned methods takes anyway into account the presence of different classes of users or demand types.

Crossmit and Green (1982) identify an ordering for water uses and thus constructed the charges with an *incremental cost allocation scheme*: the costs are first calculated for a project serving the primary purpose, then the second purpose is added and the difference in the costs for the two different projects is allocated to the second one, and so on. However the definition of a purpose as primary or secondary seems very arbitrary.

Crossmit and Green (1982) propose an allocation of costs among users based on certain CGT principles, and first of all enunciate the properties of the *Core* of an *n*-person game.

The general charge for the *i*-th user is:

$$x(i) = x(i)_{\min} + \beta(i)\left[c(N) - \sum_{i=1}^{n} x(i)_{\min}\right],$$

where $\beta(i)$ represents the rate of the remaining costs $\left[c(N) - \sum_{i=1}^{n} x(i)_{\min}\right]$ that the user should pay, $i \in N$ and $N = \{1, ..., n\}$. We have $\sum_{i \in N} \beta(i) = 1$.

The minimum cost $x(i)_{\min}$ can be considered equal to 0, to the direct or specific costs or to the separable costs (James and Lee, 1971), but can also be identified with the minimum charge for *i* defined by the *Core* bounds.

$\beta(i)$ can be (James and Lee, 1971): (1) equal for all the users, (2) proportional to a measure of use of the water, e.g. volume, (3) entirely attributed to the highest priority participant, (4) proportional to the benefit in excess of assigned minimum cost, (5) proportional to the excess cost to provide the service by some alternative means, (6) proportional to the minimum between (4) and (5).

Considering each user independently would require the evaluation of a very large number of different water supply systems, but the number of combinations can be reduced by replacing individual users with (1) zones of service areas within the boundaries of water district; (2) user classes with similar demand characteristics; and (3) demand types. The cost function can be consequently derived, even if data are not so easy to collect.

The authors consider a hypothetical example and apply their method for equitable and efficient impact fees for urban water systems in Almos. The players are grouped into medium (M) and low (L) density single-family users, and a warehouse (W), each of them considered as a single agent. Some CGT concepts are used in order to allocate costs among these users. The Core of the three-person game in question is nonempty, and the means between the minimum and maximum Core bounds for each player are selected to assign the costs. To construct fair charges based on the true cost of providing service some considerations on the use of water have to be added to the model (for example indoor use, outdoor use and fire use for each group of users).

IRRIGATION

In Nakayama and Suzuki's paper (1976) we find a typical cost allocation problem for a joint enterprise (agricultural – urban water supply) and the proposed model is a *TU-cooperative game* where the *Nucleolus* seems to offer a reasonable solution as a cost-sharing rule. This work has a certain relevance, considering it is one of the first applications of the CGT tools to a water resources management project. In more recent literature we find some *NTU* models also.

In the proposed model, the *N* players of the game are partitioned into two subsets: *A*, consisting of agricultural associations, and *B*, consisting of city services. Each city *i* in *B* requires an additional annual quantity of water δ_i ($\delta_i = 0$ if $i \in A$), and can choose among: (1) constructing a dam with or without the cooperation of other cities and (2) making an agreement with the agricultural associations for the direct diversion of water from them to the city or (3) a combination of (1) and (2).

A cooperative game is constructed and the concept of *Nucleolus* is introduced as a 'fair' division of costs among participants in a joint project.

The proposed case study is about Kanagawa prefecture in Japan, where a dam will be built and costs will be allocated among two agricultural associations and three city services:

$$N = \{1, 2, 3, 4, 5\}$$

$$A = \{1, 2\}$$

$$B = \{3, 4, 5\}$$

The cost function is determined through a linear programming problem, and the question turns to how to determine a fair apportionment of $v(N)$ among the different players.

The authors require for a solution the properties of (1) *efficiency*, (2) *individual rationality* and (3) *group rationality*, and introduce the Nucleolus: "However it might be that no allocations satisfying (1) and (2) also satisfy (3). This being so, any ‘fair’ allocation will simply have to come as ‘close’ to meeting (3) as possible. One notion of ‘close’ leads to the Nucleolus of a game (…)”.

The case study is considered and the Nucleolus of the Kanagawa Prefecture game is calculated solving a linear programming problem. The authors don’t comment on the numerical results of their paper.

Ratner and Yaron (1990) examine the consequences of the choice of a *TU*- or an *NTU*- framework: the possibility of *side payments* has a relevant political, economic and social impact on the players. They apply their analytical framework to a regional cooperation among farmers dealing with water quality. The conclusion is that even if regional cooperation with side payments could provide a better increase in the income, in practice it is preferable to aspire to the NTU gain, which is less than the amount under the transferable utility hypothesis. The reason is that the farmers would not accept the side payments policy, where a share of the income generated by the most efficient farm should be transferred to another one; beside this concern, another question is which part of this gain has o be transferred? It is a hard work to find an allocation of the surplus of the gains that are able to get a certain acceptance among the players.

The Nash-Harsanyi approach seems to be the most appropriate for the conditions studied.

Water quotas, whose allocation was often stated long ago, may now prove to be inefficient.

An interesting problem arises when the regional authority gives a region the opportunity of increasing the salinity of the water supply to the region and to be compensated by an increased quantity: the determination of the optimal mix, when different regions have different desired Quantity-Salinity (Q-S) mix, is the aim of this paper.

The water scarcity problem, together with inefficiency issues emphasized the need for inter-farm and inter-regional cooperation for water mobility.

Once determined the maximum income for the region, through a linear programming model, two possible income distribution policies are considered: with or without side payments.

In the model without side payments the cooperation is restricted to the exchange of water quotas; in the other one direct income transfers are allowed.

The models discussed are applied to the analysis of a potential cooperation among three farms in the Negev area of Israel. The allocation of the gain, under the TU-cooperative model, is computed through the *Nucleolus*, the *Shapley value* and the *shadow cost pricing*, while the situation without side payments is modelled with a *Nash-Harsanyi* approach.

Whereas a priori the shadow pricing method can seem reasonable, some problems occur because the price of water for the farmers is often subsidized and even lower than the shadow price.

In the NTU-framework the problem is to identify a point on the efficiency frontier and the authors follow the approach proposed by Nash (1950) for two players and generalized by Harsanyi (1959) for n players with $n > 2$. This approach consists in the maximization of Z (where y_i denotes income to farm i and $y_i^{\,0}$ is the income for the same firm, without the cooperative agreement):

$$Z = \prod_{i=1}^{n} \left(y_i - y_i^0 \right).$$

Some assumptions (corresponding to the axiomatic characterization of the Nash-Harsanyi solution) underlie this approach: joint efficiency, invariance with respect to linear utility transformations, symmetry and independence of irrelevant alternatives.

A quasi-empirical application of the different models is proposed for three farms in the Negev Area of Israel: the authors explain that all the data are real, except for the ‘boundaries’ of the region.

The results under the different assumptions are presented and compared: the authors conclude that an increase of 17% could occur to the regional income though cooperation with side payments; on the contrary the region can get an increase of 8% if cooperation does not involve side-payments.

On the other hand some difficulties may arise from the side payment policy (see introduction), while the model without side payments seems to be more reasonable: its assumptions are simple and easy to understand, and for this case study it is computationally simple.

If compared with most CGT application literature Aadland and Koplin follow a mirror-like approach in their two following papers (1998, 2004). Their analysis deals with some real-world cost-sharing rules for irrigation (they consider the case study of 25 irrigation ditches in Montana) and they try to see these rules under a game-theoretical point of view, providing in the first paper an ex-post axiomatic characterization. The mathematical tool does not prevail over reality: it is at its complete disposal. The problem in the use of axiomatic approaches and of the deriving solution concepts is that a reasonable axiom can be too restrictive or even cause unreasonable outputs for certain real situations. 'Fairness' also, on the authors' opinion, has to be intended as long-term acceptance by people judgment. In their second paper Aadland and Koplin, while reexamining the same case study ask to themselves if there is a correspondence between some environmental aspects and the choice of a certain allocation rule by the farmers; they try to answer with the aid of an econometric model.

In his paper Dinar (2001) presents a cooperative bargaining model with NTU, and uses the Nash solution because "The allocation is feasible, fulfills Individual Rationality, is Pareto optimal, symmetric, non related with nonrelevant alternatives and to a specific presentation of the VNM utility function." The peculiarity of Dinar's model is that it allows an optimization of the capacity of the joint facility simultaneously with the cost allocation procedure.

The article by Norde et al. (2003) deals with another branch of CGT—*fixed tree games*. In some irrigation systems it can be helpful to model the situation as a *tree* where the farmers are located on one (or more in the case of FRP games) vertex, and it is possible to construct a corresponding cooperative game. The paper is almost theoretical but it is presented to give the reader an idea of a different CGT tool, which can be employed in modeling some irrigation water supply networks.

A work by Aadland and Koplin (1998) examines cost-sharing arrangements in a sample of twenty-five irrigation ditches in south-central Montana. These arrangements—variations of serial and average cost sharing—often date back to the corresponding ditch's construction at the turn of the century. The authors present an empirical and axiomatic analysis of the allocation mechanisms employed by the ranchers in the region, using a list of static and dynamic equity principles as was revealed by direct phone surveys. The analysis shows that the observed cost-sharing arrangements can be characterized as unique solutions to equity-constrained welfare maximization.

The cost-sharing rules dominating the case study, the *serial/Shapley* and *average cost-share* rules, have been kept surprisingly stable, suggesting that they are really perceived as 'fair' by the players. This motivates the authors' efforts to construct characterizations of the sampled mechanisms based exclusively on principles of equity.

While collecting the data, the authors directly made phone calls to one or more irrigators along each ditch, asking about (a) details regarding the cost-sharing arrangements currently in use, and (b) general feeling about what can be considered to be fair methods of sharing irrigation costs.

Two classes of sharing rules dominated: *average cost sharing* (egalitarian) and *serial cost sharing*. The average cost-sharing rule simply takes the total cost of ditch maintenance and divides it equally amongst all users. The serial cost-share rule divides the cost of maintaining each ditch segment equally among all agents that require the use of this segment to meet their irrigation needs. As in the '*airport games*' of Littlechild and Owen (1973), the allocation offered by the *serial rule* is identical to that prescribed by the *Shapley value* of an appropriately defined cooperative game. Per acre and per water-share weighted variations of restricted average and serial rules were also found in the case study, and axiomatically characterized.

Dinar (2001) introduces into an allocation game of a joint groundwater development both the size and the equity considerations, in a stylized example. The paper presents an application of the Nash model to a combined problem of optimal development of a joint facility (determination of the optimal capacity) and related cost-benefits allocation considerations. Two alternative modifications and a diagrammatic procedure are developed. The conditions for an optimal Nash solution are derived. The paper proposes a procedure allowing to deal simultaneously with capacity optimization and cost allocation. *The Nash solution* to a cooperative bargaining problem can fit this kind of situations, giving an axiomatic unique allocation to a cooperative problem between two players. (The Nash model has been generalized for *n* players by Harsany (1959, 1986). Two alternative Nash models are developed: Model A is the classical Nash model for a two-person bargaining game; Model B follows the modification proposed by Harsanyi and, even if in the case study there are only two players, it can provide an efficient solution when more than two participants are involved also.

The paper shows that the two models produce similar solutions, under a similar set of choice variables. The hypothetical case study deals with two agricultural producers wishing to cooperate for a new water source, e.g. a well; each farmer has his own water supply limit, demand, and technology. By including in the algorithm a negative service fee, the model allows the transfer of income from one player to the other; in this case the degree of economies of scale is such that it provides the other player with the appropriate level of incentives for cooperation.

Hamers, Miquel, Norde, and van Velzen (2003) apply CGT to a problem of allocation of maintenance of an irrigation system. They introduce fixed tree games with repeated players (FRP games), which are a generalization of standard fixed tree games. This generalization consists in allowing players to be located in more than one vertex. As a consequence, these players can choose among several ways of connection with the root. The authors show that FRP games are balanced. They prove that the core of an FRP game coincides with the core of a related concave fixed tree game, and show how to find the nucleolus and we characterize the orders which provide marginal vectors in the core of an FRP game.

The FRP game in this paper is a generalization of the *fixed tree problem*, introduced by Megiddo (1978), where the players may be located in more than one vertex of the given tree. A *fixed tree problem* consists in a *rooted tree* Γ and a set of agents N, each agent being located exactly at one vertex of Γ and each vertex containing only one agent. Megiddo (1978) associated this problem with a *cooperative cost game* (N, c), called a *fixed tree game*, where, for every coalition $S \subset N$, $c(S)$ denotes the minimal cost needed to connect all members of S to the root via a *subtree* of Γ.

As a motivation for this generalized model one can consider for example the following irrigation problem. Consider a set of parcels in a desert environment, which need to be irrigated from a well. For that reason, a network has been designed which allows the conveyance of water from the well to at least one of the corners of each parcel. Consider the situation with eight parcels in figure 1.

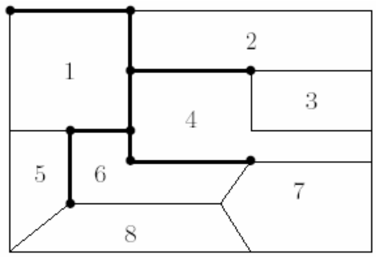


Figure 1: The Irrigation network in a Perimeter

Bold lines indicate the network that has already been made up. The players are facing the problem of dividing the maintenance costs of this network, so they are facing a fixed tree problem where the tree is as depicted in figure 2 below.

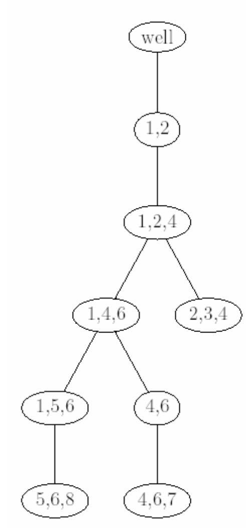


Figure 2: The fixed tree irrigation problem

The concept of *Core* of a *cost game* is recalled, and constructed below.

A fixed tree problem with repeated players (FRP), in the game described above, is a 5-tuple:

$\Gamma = \left(N, (V,E), 0, \left(S(v)\right)_{v\in V}, \left(a(e)\right)_{e\in E}\right)$, where:

$N = \{1,2,...,n\}$ is a finite set of players.

(V,E) is a tree with vertex *V* and edge set *E*.

0 is a special element of *V* called the *root* of the tree.

$S(v) \subseteq N$ is for every $v \in V$ a (possibly empty) subset of players occupying vertex *v*.

$a(e) > 0$ is for every edge $e \in E$ the cost associated with edge *e*, which satisfies the following assumptions:

(A_1) for every $i \in N$ there is a $v \in V$ with $i \in S(v)$

(A_2) for each leaf $\mathrm{t} \in V$ there is an $\mathrm{i} \in N$ such that $i \in S(t)$

and $i \notin S(v)$ for every $v \in V \setminus \{t\}$

The authors show that *FRP games* are *balanced* and they focus on the structure of the *Core*. (Standard *fixed tree games* are known to be *concave*, consequently these games are *balanced*. The *Core* of these games is not empty.)

While the papers discussed so far assume that the cost allocation schemes operate in neutral environments, one knows that this is not always the case and that the environment affects the effectiveness and stability of the allocation schemes. Aadland and Koplin (2004) use shared irrigation costs as a context for examining the extent to which the structural environment explains the selection of a cost sharing rule. They find that environmental factors that - induce greater dependence on the cooperation than others, influence majority interests, create difficulties for interpersonal utility comparisons, or impact notions of "fairness" - all have impressive explanatory power. In this work, as in Aadland and Koplin (1998) examine some 'real-world' cost-sharing rules, trying to understand how the environmental context can influence them and make them more or less stable.

The case study and thus the examined cost-sharing rules are the one of the previous paper, but here the authors better enter into details of the data and collecting data instruments and try to answer some further questions.

Multiple sharing mechanisms can often be observed coexisting harmoniously in seemingly identical environments. Does such behavior suggest that several sharing mechanisms are equally appropriate and the choice of which to adopt is essentially arbitrary? Or do environmental cues exist that reliably reveal the sharing mechanism of choice? If such explanatory power can be empirically established, does it support or run counter to the central spirit of axioms employed in the theoretical cost-sharing literature?

The *average class* rules distribute total costs equally per capita, per acre, or per shares of stock owned. The *serial class* rules share total costs either serially per capita, per acre, or per shares of stock owned or agents pay only for costs incurred on their property. The serial class contains those rules that protect agents from the burden of costs incurred downstream from their property, a principle the authors refer to as *excess demand protection* (EDP).

An econometric analysis reveals that the choice of a rule is not arbitrary and can be explained through a reduced form of the structural environment. Some peculiar environmental aspect can make EDP more (less) compelling, and the rules in the serial (average) class become more likely to the players.

The developed econometric model assumes that the farmers choose between the two classes of rules depending on structural environmental characteristics, under this formula:

$$Y_i = X_i \beta + \varepsilon_i$$

where:

Y_i = latent variable measuring the likelihood of choosing either the serial or average cost-sharing class of rule for ditch *i*,

X_i = row vector of explanatory variables for ditch *i*,

β = column vector of coefficients

ε_i = normally distributed error term with mean equal to 0

The authors conclude that the estimated coefficients are nearly all statistically significant and the signs are generally in agreement with expectations. Moreover, the overall fit of the model is excellent.

HYDROELECTRIC POWER

While hydroelectric plants are a very important endavor in the water sector among political jurisdictions (states, provinces) sharing the same water source, and sectors using the services of thes plants, the literature is suprisingly poor in CGT applications. Gately (1974) provides a very comprehensive example of the allocation of both the electricity and its cost of production among Indian states that can potentially share hydroelectric plants. Water is quite marginal in this article, but the paper introduces the new concept of players' *propensity to disrupt* a coalition, recalled by many other authors in CGT literature.

The paper focuses on the problem of determining a mutually acceptable division of the gains from regional cooperation, with reference to planning investment in hydro-electric power in the Southern Electricity Region of India. It calculates the costs of providing power to the region of the case study under different assumptions about the degree of cooperation and considers some mutually accepted cost allocations. The region has been divided into three areas, and the five possible coalition structures (corresponding to different degrees of cooperation) are considered: complete cooperation among all states, self-sufficiency for all states and partial cooperation among the states.

The difference between an area's costs under self-sufficiency and its costs under a given coalition structure states its payoff from that coalition structure and provides the characteristic function. When this difference is negative it would be irrational for that area to cooperate. The GT concepts of *imputation* and *Core* are introduced to characterize a vector of final payments.

The Core of the game is non-empty, and the idea of "*propensity to disrupt*" is introduced to select an imputation inside the Core. For any proposed imputation, area *i*'s *propensity to disrupt* the three-area agreement is the ratio of how much the other two areas would lose if area *i* refused to cooperate to how much it would lose if refused to cooperate. Even after employing the disruptive propensity concept to eliminate those core imputations where only one area's final payment is "too small" there still remains a wide range of mutually acceptable ways of sharing the gains of cooperation.

The paper examines the possibility of (1) Equal shares, (2) Equal ratio of total final costs to costs under self-sufficiency, (3) Kernel, (4) Demand weighted shares, (5) Shapley value and (6) Equal propensity to disrupt. The first two cost allocations are not in the Core; the third, defined by the author "naively 'equitable'" does not take into account the different bargaining power of the areas; (3) and (4) can provide a Core allocation, but some area's propensity to disrupt might result too high; (5) for the case study is in the Core and gives small propensities to disrupt; (6) leaves each area equally satisfied, in terms of propensity to disrupt. Among the considered cost allocation schemes the Shapley value and the one with equal propensities to disrupt can be considered mutually acceptable.

WATER POLLUTION

In this section we include some CGT application on pollution, and specifically pollution control and prevention. Cost allocation for polluted water treatment will be dealt separately. We made this distinction because it can be useful to see how different approaches to the problem of water pollution, can be managed with cooperative game theoretic models.

In the paper by Kilgour et al. (1988) a water management authority fixes a maximum allowed load for COD (Chemical Oxygen Demand) for a certain water body, and later distributes "COD quotas" among the dischargers. Thus, the allocation is of the pollution allowance agreed among the polluters (cities), and they have an economic incentive for cooperation in COD reduction (by joint management and projects). A new regulatory system for water quality is described, analyzed and illustrated with its main properties.

BOD (Biochemical Oxygen Demand) and COD standards, like pH, suspended solids and phosphorate phosphorus can be relevant quality criteria. However, for other toxic pollutants separate and often specific methodologies are required. Furthermore, empirical evidence suggested that a criterion based on the total amount of pollutants should be more useful than conventional concentration limits: this solution can be called "*load control*" to distinguish it from "*concentration control*". (This is reasonable, for example, if we deal with 'closed' water systems where the load effect is more relevant.)

Finding the right quality criteria is not sufficient. The 'fairness' of the division of total load among polluters can become a difficult social and political point. Cooperation may provide a reasonable solution. The load function is approximated by a formula that fits most of the COD data with a reasonable accuracy, and it is shown that cities can very often reduce load more efficiently by sharing the effort.

A general system for load control is described: the central authority can reach its goal on a certain COD load by selecting, for each city *i*, a proportional quota p_i satisfying:

$p_i \geq 0$ for all $i \in N$, and $\sum_{i=1}^{n} p_i = 1$. Further, the central authority must require that each city spend an amount x_i, so that $v(S) = -\min\{x : L_S(x) \leq Ap_S\}$ (where A is the maximum load accepted and *L* is the load function).

The cities, as the authors show, will tend to cooperate to reduce load efficiently. We can define the quota for a cooperating group of cities, or coalition $p_S = \sum_{i \in S} p_i$, and thus, the requirement seen above can become $L_S(x_S) \leq Ap_S$.

Now the questions are: which coalitions will form? How should costs be split within these coalitions? The CGT model may answer these questions.

The characteristic function of a COD allocation game is $v(S) = -\min\{x : L_S(x) \leq Ap_S\}$ and the game is superadditive. An equivalent model, considering the savings game <*N*, *w*> , has the following form characteristic function: $w(S) = v(S) - \sum_{i \in S} v(i)$ for $S \neq \emptyset$. For this game the *Shapley value* and the *Nucleolus* are considered as possible solutions.

In a different paper, Dinar and Howitt (1997) conduct a pollution control analysis focusing on drainage water treatment. Different allocation schemes (proportional allocation, Nash-Harsanyi, allocation according to marginal cost, Shapley value, the nucleolus and the Separable Cost, Remaining Benefit principle) are used to allocate regional joint environmental control costs under two extreme states of nature scenarios, resulting in different pollution flows. Two different states of nature are included in the model: high flow drainage and low flow drainage in the Central Valley of California. They are been separately taken into account in order to understand what happens in terms of stability and acceptability of a solution if some natural changes occur. The results provide clear empirical evidence that regional arrangements may vary with state of nature. Another important result is that the different allocation schemes have different outcomes in terms of their acceptability of the players, and in terms of their derived stability, as measured by the Shapley-Shubik Power Index, and by the Propensity to Disrupt.

The case study is about the joint treatment of irrigation drainage water by several water districts in California and the allocation of the joint costs. The authors introduce a cooperative game with side-payments in characteristic function form. A necessary condition for an allocation to be accepted by the players is the fulfillment of the Core conditions.

Additional conditions are the stability of the coalition One measure used to assess the stability of an allocation scheme is α_i, comparing the gains to a player with the gains to the coalition.

$$\alpha_i = \frac{x_i - v(i)}{\sum_{j \in N} \left(x_j - v(j)\right)}, \quad i \in N, \quad \sum_{i \in N} \alpha_i = 1$$

Acceptability and stability are tested in two states of nature: high drainage flow and low drainage flow. In fact, the changes in water quantity to be treated have to be incorporated in the allocation scheme otherwise the solution might not encourage cooperation.

Another set of papers, (Jorgensen and Zaccour, 2001; Fernandez, 2002) deal with cooperation in *differential games* for a problem of pollution. In the first paper, roughly speaking, some properties are required to the characteristic function and to a side payments scheme on a time interval $\left[0,T\right]$. In the second one Fernandez models a transboundary pollution situation between USA and Mexico and analyzes the consequences of cooperation and non-cooperation in different scenarios of trade liberalization.

Jorgensen and Zaccour (2001) determine a rule to share a surplus gained when two countries or regions agree to coordinate their policies to reduce downstream pollution. An intertemporal decomposition scheme for the total side payment is proposed. This scheme has the following individual rationality property: in each subgame that starts along the cooperative trajectory, one country is guaranteed to receive a higher payoff in the cooperative solution than in the disagreement solution. For this country another notion of individual rationality holds. It will at any time during the play of the game receive a higher payoff in the cooperative solution than in the disagreement solution.

In a case of downstream pollution a country/region suffers from the pollution generated by its upstream neighbor(s). The authors suppose that the two countries/regions wish to make an agreement in order to maximize the sum of their respective payoffs. The surplus given by cooperation is the difference between the optimal joint payoff and the sum of the disagreement payoffs.

To distribute the surplus among the regions, side payments will be necessary and the authors require a scheme with some desirable properties in terms of individual rationality. (The assumption is that the side payment for the entire duration of the agreement is not paid as a lump sum: rather it is distributed as a continuous stream over time.)

Three different notions of individual rationality are considered: (1) overall individual rationality, (2) individual rationality in every subgame along the cooperative trajectory (time consistency), and (3) individual rationality at any instant of time.

If we denote $\left[0,T\right]$ the time interval of the agreement, (1) means that “for the entire duration of the agreement, in the cooperative solution each region receives a payoff which, after side payments, is no less than the disagreement payoff of the region”; (2) is individual rationality over $\left[\tau,T\right]$ for any $\tau\in\left[0,T\right]$, that is, time consistency of a cooperative solution (Petrosjan, 1993,1997); and (3) is individual rationality at any $t\in\left[0,T\right]$: at any instant of time the instantaneous cooperative payoff, after side payments, of each region is not less than the instantaneous disagreement payoff of the region.

Considering the case of two regions, Region 1 and Region 2, called respectively *vulnerable* and *non-vulnerable* region, according to Kaitala and Pohjola (1995), where Region 1 is only affected by its own pollution, while Region 2 is affected by pollution of both countries, whereas property (1) is easy to satisfy for both regions, they could only guarantee, in general, the satisfaction of (2) and (3) for the non-vulnerable Region 2. (Under specific circumstances, however, (2) and (3) can be satisfied for the vulnerable region, too.)

Starting from a non-cooperative scenario, Jorgensen and Zaccour, 2001 draw an intertemporal side payments scheme based on the egalitarian principle (to divide the surplus equally among the regions).

Fernandez (2002) develops a differential game to examine the effects of trade liberalization on transboundary water pollution. Water pollution is due to wastewater emissions from countries in a shared waterway. The case in question is the U.S.-Mexico border. Noncooperative and cooperative games are examined with changes in trade policy and public health damages. Results show trade liberalization leads

Mexico to curtail pollution in both games. Cooperation and trade liberalization limit emissions from both countries and curtail strategic behavior of the United States from Mexico's pollution control efforts in the noncooperative game.

In the case study application, the resource management agency chooses different types of emissions in order to maximize its net benefits for the United States and for Mexico on an infinite time horizon. The conclusion is that trade liberalization provides economic incentives to reduce pollution and reuse treated wastewater for irrigation.

WASTEWATER TREATMENT

Giglio and Wrightington open, with their 1972 paper, an important literature thread about the application of CGT to the field of wastewater treatment. A joint plant, developed by more than one agent (city, factory, …) can reduce costs without a loss of efficiency, but it is immediate to find a problem of cost allocation. Loehman et al. (1979) applying the *Generalized Shapley value* (GSV; introduced few years before by two of the authors of this paper) to a similar project for water treatment in Missouri, conclude that a cost sharing method has to be simple to gain acceptance by the involved agents and that the GSV, interesting from a theoretical point of view could be "unnecessarily complex in the light of the community needs".

We find a CGT model of a cost-sharing problem in a joint project development also in Kogiku and Sheenan (1980), Loehman (1995), Holler and Li (1996). Lejano and Davos, in the same context, (1995, and 1999) introduce the concept of *Normalized Nucleolus*, taking into account the rate of return of joining a coalition and being monotonic in a proportional manner. In the paper by Dinar et al. (1986) the gain to be shared is due to reuse of treated wastewater in irrigation.

In Dinar at al. (2003) we find the first application of *Stochastic Cooperative Game Theory* to water resource management, and specifically to an hypothetical example for development of a wastewater treatment plant: "stochastic considerations may affect the nature of the solution, depending on the attitude of the players towards risk and the nature of the (possibly not concave) cost function of the water project".

While the applications of the other reported papers have a local or regional scale, Caswell and Frisvold's presents an international case of water pollution and treatment (US-Mexico border). The framework is more complicated because of the international scale of the problem, but the authors believe that the use of a *cooperative bargaining model* can address the apportionment of costs of a waste collection and treatment systems, once minimized the costs.

Several cost sharing methods are examined and compared by Giglio and Wrightington (1972): (1) based on the measure of pollution, (2) based on single plant cost with a rebate proportional to the measure of pollution, (3) SCRB method, (4) free market bargaining, (5) bargaining including the regional authority as a participant.

In (1) the polluters are equally treated, because they pay the same amount for a pollution unit. In the numerical example one of the polluters would pay more than he should if treating his waste alone. In (2) each user has to pay his single cost to the authority, and the authority can return the difference between the funds collected and its joint costs, and the rebate is assumed to be proportional to the measure of pollution. According to this assumption, the largest polluter will receive the largest rebate, but he still pays more, in total. With the example the authors show that, probably, a bargaining process will start, making it more difficult to reach an agreement on the regional plan. Using the SCRB method (3) in the example further bargaining is no longer needed. In the section about method (4), we find an introduction to cooperative game theory, and the imputation set is described through its inequalities: the authors analyse different kinds of solution these inequalities may lead to, and conclude that "although it clarifies the situation, game theory approach does not usually provide a treatable solution to the problem". (Even if the authors use the term *bargaining*, the framework is a TU-game.) In (5) the regional authority is included in the game and the problem can be solved with the help of linear programming. The problem to be solved is the following:

$$\min \sum_{j=0}^{n} X_i = P_{\min}$$

subject to:

$$A_{11}X_1 + \dots + A_{1n}X_n \geq P_1$$
$$\dots$$
$$A_{m1}X_1 + \dots + A_{mn}X_n \geq P_m$$
$$X_i \geq 0$$

Where:

j is an index of polluter; X_j is savings returned to user j; i is index representing a coalition, $i = 1, 2, \dots, m$; P_i is payoff of coalition i; $A_{ij} = 1$ if j is a member of coalition i, and 0 otherwise. Here a solution always exists, but it's probably not unique.

The authors conclude that no method can be universally preferred, but some of them show some advantages. Methods (2) and (3) can be particularly useful in situations with few attractive alternatives.

Loehman, Orlando, Tschirhart and Whinston (1979) depart in their analysis of water pollution control in the Meramec River Basin in Missouri USA that polluters have the option of treating their pollution in a regional system or constructing separate smaller systems. In order to encourage participation in a regional system so that the economies of scale are realized, the cost allocation method employed must offer economic incentives.

The paper provides a description of the Meramec River Basin and of the main dischargers. Later a *cost-game* is constructed and the presence of an economy of scale provides *subadditivity* for the game. The primary, secondary and advanced wastewater treatment plants are examined from the point of view of their costs, in order to meet the required quality standards choosing the minimum costs.

The *Shapley value* is introduced and explained but the authors believe that "in an application to real life situations such as that undertaken here, use of this value has a few deficiencies". The main problem is that it seems to be unrealistic to consider all the coalitions equally possible. The *Generalized Shapley value*, by Loehman and Winston (1976) does not require this assumption, and will be used here as well:

$$x_i = \sum_{\substack{S \subset N \\ i \in S}} p\left(S, S - \{i\}\right)\left[C\left(S\right) - C\left(S - \{i\}\right)\right]$$

The *Generalized Shapley value* is a weighted sum of incremental costs, and in Loehman and Winston (1976) the suggestion is to get the weights from the probabilities of certain orders (p is interpreted as the probability that i joins the coalition $S - \{i\}$), replacing the usual coefficients $[(n-s)!(s-1)!]/(n!)$.

The *Generalized Shapley* charges are calculated and the result is that the charge is always less than the cost of self-treatment, but the allocation does not lie in the Core, so that some coalitions may have interests to disrupt the grand coalition. Gately's concept of (minimizing) the *propensity to disrupt* (1974) is later used to get other possible charges.

In a different paper, Kogiku and Sheehan (1980) are concerned with fair apportionment. The study of these problems is of considerable potential importance as most of the large water resource development projects are collective endeavors. Furthermore, a large proportion of waste treatment projects involve at least two major actors. In addition, in the last several years many water resource development situations have attracted the attention of a third party in the form of the Environmental Protection Agency (and/or its cousins on the State/Regional level; e.g. the Porter-Cologne Water Quality Control Boards in California). This intervention opens up a range of new bargaining outcomes wherein standard-setting government agencies allot themselves a share of the benefits of cooperation which would normally have accrued solely to the local participants.

Several ideas of fairness and several systems for apportioning costs and benefits are discussed with the help of a hypothetical case study: two polluters sited on a river, with an interest in developing a joint wastewater facility. Some rules for the cost-sharing method are discussed, using a hypothetical example as a thread for the discussion: (1) an *equal share* of the gains from cooperation; (2) a division of costs *proportional to the costs they would have paid under self-sufficiency*; (3) equalizes the *propensity to disrupt* of the participants (Gately, 1974); (4) the *Shapley value*; (5) the *Kernel*.

Dinar, Yaron and Kannai (1986) demonstrate the use of CGT to allocation of costs and benefits from regional cooperation, with respect to reuse of municipal wastewater for irrigation at the Ramla region of Israel. A regional model provides the maximal regional income from various technical and institutional options which has to be redistributed among a town that generates the pollution and several farms that may reuse it. Different allocations based on marginal cost pricing and schemes from cooperative game theory like the core, Shapley value, generalized Shapley value, and nucleolus are applied. The *Core* of this game is a four dimensional polyhedron. It is not conclusive, because it provides only bounds on the claims of the participants.

Marginal cost pricing is not applicable in this case since the number of participants in the wastewater-effluent "market" is small, they are not anonymous, and agreements and coalitions among some of the potential participants are possible; the treatment costs depend on increasing economies and decreasing marginal costs. In such a case, marginal cost pricing leads to a deficit, which would need to be covered either by the users or some external agency (e.g., government), or both.

The town and one farm of the three have the main additional gains according to all allocation schemes presented. The authors conclude that game theoretical approaches do not provide an objective, indisputable solution, to the income distribution problem, but they provide a bound for the players' claims (*Core*) and a better understanding of the situation.

Loheman (1995) extends the application of cooperative game theory to include both water allocation and cost sharing. Combining cooperative game theory and theory of market games provide answers to questions of what is the efficient allocation of water, which water supply project should be undertaken, and what should be the price of water. Cost allocation and market games are first described separately below, and then are combined for this purpose.

The author introduces some solution concepts that are based on the characteristic function (*Core*, *Shapley value*, *Generalized Shapley value*, *Nucleolus*); then reports two solutions not based on transferable utility cooperative games: the *Nash bargaining solution* and the *Generalized Nash solution* by Harsanyi (1959). A small example is used to illustrate that different solution concepts can differ significantly in terms of the distribution of gains and implied power. The example deals with four dischargers having to share costs for pollution treatment at a single location (the costs include piping plus treatment costs). A *market game* (Shubick, 1984) is later introduced to allow modeling a water allocation problem with a fixed supply source, and solved using the *Nash solution* and the *Generalized Nash solution*.

Lejano and Davos (1995) introduce the *Normalized Nucleolus* and apply it to a N-Person Cooperative game of water reuse project in Southern California. The results obtained with the normalized nucleolus are compared with those derived with more traditional solution concepts such as the nucleolus and the Shapley value.

The Nucleolus, in fact, is based on the absolute savings represented by the excess function, not taking into account the rate of return of joining a coalition:

$$e^{*}(S,x)=\left[c(S)-x(S)\right]/x(S)=\left[c(S)/x(S)\right]-1$$

In the Normalized Nucleolus, the problem to be solved is:

$$\min \ -\varepsilon$$

subject to:

$$\left\{\left[x(S)/c(S)\right]+\varepsilon\right\}\le 1 \quad \forall S\subseteq N,$$

$$\sum_{i\in N} x(i)=c(N) \quad \varepsilon, x(i)\ge 0$$

An interesting property of this solution concept is that it is monotonic in a proportional manner. For example, if the total cost increases, then the charges will increase keeping the same relative proportions to all players. A case study of water reclamation and reuse in Southern California is described and the two mentioned solution concepts together with the *Shapley value* are applied to the data, and compared. In particular, it is discussed the impact of the three different allocations on the margin of assurance that the decision will be actually implemented. It is also stressed (using the figures of the Project) the distributional proportionality of the normalized nucleolus.

Holler and Li (1996) apply N-person cooperative game theory to analyze the efficient cost allocation problem for a group of three communities constructing a common sewage system. Important solution concepts such as the core, the Shapley value, the kernel, and the nucleolus are all used to establish efficient pricing rules. Treating the sewage system as a public good, the contribution that a community should make is also measured by using the *public good power index*. The formation of subcoalitions and the equilibrium coalition structure are investigated and discussed for the case that the splitting method is accepted to be a fair distribution rule. A model of a cost allocation problem for a joint sewage processing system is described. The paper compares the different solution concepts to show how a fixed distribution rule can prevail throughout the bargaining process between the communities and to analyze the equilibrium coalition formation resulting from this bargaining process.

Lejano and Davos (1999) suggest that many environmental management issues can be defined as allocation problems, e.g., the allocation of rights to use common-pool resources or the allocation of the cost of regional resource development projects. As such the allocation methods developed in the area of cooperative N-person game theory are most appropriate for these problems because they focus on the conditions for engendering and sustaining the necessary cooperation among the involved stakeholders. These solution concepts seek to ensure that the allocation is based on some norm of equity and, most often, also to minimize the incentive for any player to defect from the cooperative venture.

The authors' introduction to this paper is about *Common Pool Resources* (CPR) management and *the Tragedy of the Commons*; they also introduce the payoff matrix of a *two-player CPR non-cooperative game*. After a description of an example involving two towns whose wastewater and runoff impact a nearby lake, they enter cooperative game theory and describe some of the main concepts, useful for a cost-sharing problem. The solutions are applied to a case study of an inter-jurisdictional water reuse project in Southern California, where a new supply of industrial quality water is being considered by taking effluent from a city's wastewater treatment plant and treating it in order to reach the quality needed for various industrial and commercial uses.

The different allocation methods are discussed, applied and commented, focusing also, at the end, on the difficulties that can arise to get appropriate information, and on the issue of fairness.

In quite a different setting, Caswell and Frisvold (2000) introduce the issue of transboundary water pollution between the US and Mexico in Southern California. In addition to the pollution problem, the work also introduces the possible incentives associate with the NAFTA agreement. New institutions created to address environmental concerns over NAFTA offer the promise of greater financial and technical assistance for water management in border cities. The paper reviews US-Mexico border water issues and institutions. Using insights from game theory, it draws policy lessons for institutions funding border water projects. The paper examines how the design of assistance programs, technical support, and pre-existing water rights and regulations affect project outcomes. The diversity and geographic dispersion of water conflicts suggests potential for applying the interconnected game approach to US-Mexico water negotiations.

The authors analyze the main features of trans-boundary management on the US-Mexico border and the different agreements throughout the years. Then, they model the border water management as a *cooperative bargaining game*. This approach is used to examine negotiated outcomes of pollution control projects in three border metro areas: San Diego-Tijuana, Calexico-Medicali and Laredo-Nuevo Laredo.

The use of a cooperative bargaining model can address the apportionment of costs of a waste collection and treatment systems, once minimized the costs, keeping in mind particular objectives.

The authors use this variant of the *Nash product*:

$$N = \left[u_m\left(\beta b - \alpha c\right) - \underline{u}_m\right]\left[u_u\left(\left(1-\beta\right)b - \left(1-\alpha\right)c - \underline{u}_u\right)\right]$$

where b and c are total project benefits and β and (1 - β) are respectively Mexico's and USA's share of benefits, and α and (1 - α) the equivalent for costs.

If the project objective and least-cost means of meeting that objective are agreed upon, then b, c and β are exogenous and the sole bargaining parameter is α, Mexico's cost share. If an equal cost sharing rule is a binding constraint, however, the bargaining process takes the form of choosing b, c, and β to maximize N subject to $\alpha = 0.5$. Sometimes, such a condition may prevent a cooperative solution: for example, it is biased against finding a cooperative solution for a joint project with high relative benefits for USA and large absolute benefits (to the extent that b/c is closer to 1 where $b - c$ is large). Some projects were also abandoned because Mexico's rate of expenses was over its budget possibilities. On the other hand, a common facility for wastewater treatment across the border can significantly reduce costs.

Negotiations over terms of a proposal may be modeled as a sequential bargaining game with exogenous risk of breakdown. One player makes an initial proposal that specifies how grant funds will be allocated. The other player accepts or rejects the offer. Players make counter proposals until they reach an agreement or negotiations end without agreement. Bargaining could end if the funding agency decides to fund competing proposals. Delays in reaching an agreement increase the probability that funds will go to other projects instead.

The *bargaining game* can be solved by:

$$N = \left[v_m\left(\mathbf{x}, \alpha A\right) - \underline{v}_m\left(\underline{\mathbf{x}}, \alpha A = 0\right)\right]^{\beta} \times \left[v_u\left(\underline{\mathbf{x}}, \left(1-\alpha\right)A\right) - \underline{v}_u\left(\underline{\mathbf{x}}, \left(1-\alpha\right)A = 0\right)\right]^{1-\beta}$$

Where: N is a *Nash product*, v_m and v_u are the city's utilities if they receive the assistance, $\underline{v}_m$ and $\underline{v}_u$ the city's utilities if no agreement is reached, A a measure of the value or size of the assistance package, α the city m's share of the assistance package, $\boldsymbol{x}$ the vector of bargaining parameters, $\underline{\boldsymbol{x}}$ the values of parameters in the event negotiations breakdown or the granting agency decides not to consider the project, and β a parameter measuring the bargaining power city m relative to city u.

At the end, *interconnected games* are introduced because a situation of *unilateral externalities* tends toward a *victim pays* outcome (Bennett et al., 1997). Bennett et al. (1997) find victim pays regimes unsatisfactory because they run counter to the polluter pays principle accepted in the international community and because countries may wish to avoid appearing to be weak negotiators. A third criticism is that with extreme income disparity, a downstream country may not be able to offer side payments to discourage the upstream country from polluting or diverting trans-boundary waters. An alternative to side payments or accepting externalities is to link negotiation issues.

Dinar, Ratner and Yaron (2002) point out some major difficulties, which arose in the authors' attempt to apply CGT concepts to two empirical problems. These difficulties tend to be general rather than specific to the problem studied. The first study (Dinar, 1984; Dinar, Kannai and Yaron, 1986) concerned a regional project designed for wastewater treatment and reuse as an irrigation water supply. The game consists of a *transferable utility situation* (side payments). At first the efficient solution (maximal regional income) has to be found; the second stage considers the redistribution of income among the participants. (The *Core*, in this case, is a four dimensional polyhedron and it may serve as a guideline for arbitration also referring to other allocation criteria.)

The second study (Ratner, 1983; Yaron and Ratner, 1985, 1990) deals with regional inter-farm cooperation in water use for irrigation and the determination of the optimal water quantity-quality (salinity) mix for each of the region's water users. Salinity is due to an inefficient allocation of water quotas. One possible way to increase the efficiency of water allocation among farms within regions is through the voluntary establishment of regional water associations or farmers cooperatives that will allocate water quotas in an efficient way, which is usually identified as non transferable utility case. (The potential for additional income due to cooperation is higher when side payments are possible.)

In the first study a real problem and real players are presented; in the second study, only the farms considered are real and the study attempts to explore the potential for inter-farm cooperation which does not yet exists. In the two case studies reviewed, each addressing a real life problem of considerable concern to farmers and policy makers, game theory approaches did not provide indisputable solutions to the cost/income allocation problems.

In a NTU situation of a three-farm cooperative the *Nash-Harsanyi solution* is deduced. The *Core* is quite large. Furthermore it is not a convex set. One may wonder if the Core is a practical concept applicable in situations such as the one dealt with in this work.

Dinar, Moretti, Patrone and Zara (2003) introduce stochasticity into the analysis of water projects by means of CGT. They depart from the observation that water resource projects are subject to stochastic water supply patterns, which affect performance, sustainability and stability of any use arrangements among participants. Traditionally, cooperative game theory has been applied to a variety of water resource problems assuming a deterministic pattern of supply. This has lead to design and interpretation of allocation schemes that are somehow limited in scope, suggesting that some solution concepts are not possible. They have applied a stochastic game theory framework, to demonstrate how stochastic considerations may change the solution, depending on the attitude toward risk aversion of the potential users and the nature of the cost function of the water project. Specifically, they show that in a game with some risk adverse players the core of the game is nonempty even if in the game with the same cost function but different attitude of the players toward risk, the correspondent core is empty.

The stochastic nature of the problem not only affects the issues of optimal design, but also can concern the allocation methods for costs and benefits. Players' attitude toward risk is considered in the model, too. The authors use a hypothetical example to show that it is possible that in the case of a deterministic game the *Shapley value* is not in the *Core*, while by including in the analysis stochastic considerations the Core conditions do change.

GROUNDWATER

The three following CGT applications to groundwater management use *bargaining* approaches to model possible cooperation in the considered aquifers. It's not a coincidence that an NTU situation has been chosen by all of the authors of the reported works for an application to groundwater, as it is not a coincidence that few cooperative models are present in the literature for groundwater. Even the works presented here raise some doubts about the practical possibility of binding agreements, and a non-cooperative model is presented alongside the cooperative one. The difficulties arising while dealing with groundwater include asymmetric information, uncertainty of water rights, environmental degradation, sustainability, high costs of control, etc.

Szidarovszky, Duckstein and Bogardi (1984) studied the management of a regional aquifer aiming at achieving multiobjective management goals. The aquifer of the presented case study is a regional groundwater in the Transdanubian Karstic region in Hungary and the conflicting objectives are with three competing sectors, namely mining, water supply and environmental protection. The method used is a generalization of Nash's cooperative game theoretical model, and may lean on Zeuther's bargaining problem. The authors present the mathematical model and numerical results are compared with the one reached for the same case study by compromise programming with an l_1-*norm* (Duckstein, Bogardi and Szidarovsky, 1979).

Most solution concepts are subjective in terms of weights, bounds, distances. In this paper the authors provide a solution based on a certain set of axioms leading to a unique point: once accepted those axioms and stated the *status quo*, the decision maker will have to accept the solution also.

A multiobjective programming problem is formulated by the authors as follows:

$$\max_{u \in U} \phi(u)$$

where u is the decision vector,

$\phi = (\phi_1, ..., \phi_n)$ is the vector valued *objective function*,

n is the number of objectives.

Here the set $L = \{\phi | \phi = (\phi_1(u), ..., \phi_n(u)), u \in U\}$ denotes the *feasible set* and $\phi^* = (\phi_1^*, ..., \phi_n^*)$ is the status quo point (*disagreement point*).

Two bargaining models are applied: the one by Zeuthen, based on the principle that the next concession within the process always comes from the objective having least maximal risk in conflict, and the one by Nash-Harsanyi (Harsanyi, 1959), satisfying Nash's axioms. (Both models require the acceptance of the mentioned assumptions.)

The objective functions are described in detail and the problem is solved. Comparing the output by the game theoretical models and the one by the compromise programming with an l_1-*norm* (Young, 1994a) the authors could not provide preference between the solutions since the two methods follow different paths to account for the preferences of the decision maker, and consequently lead to different results. The compromise programming solution incorporates preferences under the form of weights in an l_1 *distance*, while the cooperative game objective function is a *geometric distance*.

In another work, Netanyahu Just and Horowitz (1998) address the conflict over the Mountain Aquifer between Israel and the Palestinians. Sharing of the Aquifer between Israel and the Palestinian Authority is considered. Since 1967, the management of the Mountain Aquifer has been under the unilateral control of Israel. The new peace accord, however, have begun a shift in control of parts of Judea and Samaria to the Palestinian Authority. This may divide control of the Mountain Aquifer between Israel and the Palestinian Authority. Without cooperation, overpumping and degradation of water quality are likely.

The authors give an overview on Israeli and Palestinians water problem: a significant increase in water needs in the region can be faced through an improvement of water quality for existing water resources, water desalination, wastewater recycling, water conservation, and cloud seeding.

For an efficient allocation of water, a bargaining approach is considered superior to pure market solution not only because infrastructure is insufficient for markets to operate efficiently but also because common property problems cannot be resolved efficiently by markets without public intervention.

The Nash bargaining solution maximizes the Nash product $\left[u_i - \overline{u}_i\right]\left[u_p - \overline{u}_p\right]$, where *i* and *p* stand for Israelis and Palestinians. The utility functions are drown by the authors and the problem is solved. The Nash bargaining solution, in this case study, is highly robust to changes in the assumed parameters, but a *non-cooperative bargaining* framework seems to better fit the real situation.

But binding agreements in this case may not be possible because (i) groundwater property rights are ambiguous and (ii) enforcement is difficult or impossible due to lack of enforcement agencies, limitations of technology, inadequate punishment for deviations, and high costs of monitoring.

The results show that the bargaining solutions implied by game theory are robust with respect to demand elasticity for water, user cost, and cost of pumping. Further considerations of potential strategic behavior and defection show that risk of breakdown in negotiations and impatience in realizing benefits of the agreement are also important. Because of limited empirical information, the analysis at this point is illustrative and demonstrates the rule of various factors and potential behaviors.

In a recent paper Just and Netanyahu (2004) apply an interconnected game theory to common pool resources, using the Mountain Aquifer shared by the Israelis and Palestinians. One approach, the linkage approach, has been proposed in real world negotiations. The paper demonstrates that by linking issues with reciprocal importance (benefits) to the parties through interconnected games, one may avoid outcomes that stem from the 'victim pays' nature of certain situations. Because of the the imbalance of power and access between the parties, Just and Netanyahu (2004) suggest that the linkage between negotiated issues rather than water will actually eliminate a solution in the case of the Mountain aquifer between the Israelis and Palestinians.

Another international aquifer case—the Jueco Bolson aquifer between Texas-Mexico—has been analyzed by Montgomery, Nakao and Wichelns (2002). The aquifer provides municipal water supply for El Paso, Texas and Ciudad Juarez, Mexico. The aquifer lies beneath the international border, and both cities operate independently regarding pumping rates and withdrawals. Over-pumping causes an increase in the salinity of water remaining in the aquifer from mud interbeds, degrading groundwater quality.

The potential gains from cooperation include reducing the negative impacts of externalities involving pumping costs and depletion of a nonrenewable resource. The authors examine the potential gains from cooperation in the withdrawal of water from the aquifer. Four dynamic scenarios are considered: 1) a status quo scenario in which both cities continue extracting groundwater as they are at present, 2) a Nash non-cooperative game scenario, 3) a Nash bargaining scenario, and 4) a scenario that involves maximizing the sum of net benefits in both cities. All scenarios, including the non-cooperative game, provide a longer useful life of the Hueco Bolson aquifer than does the status quo. In the Nash bargaining scenario, both cities gain from cooperation and the sum of net benefits approaches the maximum that can be obtained by maximizing that value explicitly.

The interaction between the two involved cities is described through per-unit pumping costs that increase with pumping lift, as the volume of water remaining in the aquifer is reduced; the net benefits from groundwater pumping in each city is derived.

Focusing on the cooperative models (scenario3 and 4), in (3) the *Nash product* to be maximized is $\max\ \left(J_1, J_2^{Th}\right)\left(J_2 - J_2^{Th}\right)$, where $\left(J_1^{Th}, J_2^{Th}\right)$ is the net benefit values obtained in the non-cooperative game scenario.

In (4) a social planner's goal is to allocate water between the two cities thus maximizing the sum of net benefits obtained over the time. The results obtained when maximizing the sum of net benefits in this problem are similar to those obtained in the Nash bargaining scenario.

ALLOCATION OF WATER RESOURCES

In the following papers water itself, instead of costs and benefits (e.g. money for a joint project), is the medium to be allocated. In these works a common assumption is that one cannot rely on an efficient market, thus the authors consider the consequences of a game theoretic based allocation.

In the paper by Braden et al. (1991) a (thin) spot market is analyzed and the focus is on the bargaining rules that bring about an efficient solution, while in the other reported papers in this section we are in a *transferable utility* framework and some CGT tools like the *Core* and the *Shapley value* are used in order to draw an acceptable allocation.

Braden, Eheart and Saleth (1991) apply a multilateral Nash bargaining model to the Crane Creek Watershed of Kentakee County, Illinois. The authors observe that markets for water rights, which have long been advocated to resolve user conflicts and to improve efficiency are too rigid. Instead, rental or spot markets for water can improve efficiency by allowing allocational adjustments in line with changing conditions without disturbing the base right system.

They consider a small watershed, whose stream system is shared between eight farmers. Assumptions about (1) certainty about the total water available for irrigation, (2) a strictly enforced water rights system, specifying seasonal water withdrawal of each farmer, and (3) definition of water rights in terms of consumptive use, suggest that binding flow constraints make some transfers infeasible.

According to the authors, neither a cooperative nor a competitive behavior is sufficient to realistically describe water exchanges in a thin market. This is the reason why they prefer to use a multilateral bargaining model, based on the contributions of Harsanyi (1986), Zeuthen (1930) and Nash (1950).

The total gain from water trade can be shared among the n players in many ways, depending on the bargaining rules and bargaining environments.

Harrison and Tisdell (1992) are concerned with the distributional consequences of alternative methods of allocating transferable water licenses in Queensland, Australia. The equilibrium of a number of different cooperative games is used to judge which method of initial allocation of water entitlements potentially produces the most equitable distribution of the income derived from the regulated water.

Water entitlements, in Australia, are often tradable, the authorities believing that market forces can lead to an efficient and equitable redistribution of the water entitlements. The market can provide individual equity, but there is no guarantee that the market redistribution of income derived from the water will be equitable according to any particular definition of social justice.

The study adopts a cooperative game model in characteristic form with transferable utility. A number of different *n*-person cooperative games are used to estimate the distribution of income after trade among six representative farms selected from the Border River region of Queensland. The potential distributive consequences of four different allocation methods are assessed on the basis of trade between these farms. The authors consider the allocations of the *Nucleolus*, the *Shapley value*, and a *maximin allocation*. A *Rawlsian criterion* of social justice, consisting in maximizing the welfare of the worst off member, is used to assess the relative distributive justice of the alternative allocation methods.

Suppose that individuals in a social state are ordered in terms of their welfare in a social state x; if the welfare of the individuals in society is *lexicographically* ordered, then x_i is the welfare of the individual in position i. For two social state vectors x and y, the Rawlsian lexicographical rule would argue that $x > y$ (i.e., social state x is preferred to social state y) if and only if there is some individual j ($1 \leq j \leq n$) such that $x_j > y_j$, and for all $i < j$, $x_i = y_i$.

The 'optimal' payoff vector within the Core, which maximizes the payoff of the worst off player, can be estimated by:

$\max \sum_{i=1}^{n} \log(x_i)$, subject to Core condition constraints.

While such payoff vector comes unlikely from trade, as players would have to be completely altruistic for such an outcome to occur, it may be the appropriate point of comparison among alternative market outcomes.

Ambec, S.; Sprumont (2000) suggest a welfare allocation scheme among river riparians, who have quasi-linear preferences over water and money. The paper addresses efficiency, stability (in the sense of the core), and fairness (in a sense to be defined) considerations of the allocations of water and income. A cooperative game associated with that problem is shown to be convex. Using the fairness requirement that no group of agents (riparians) should enjoy a welfare higher than what it could achieve in the absence of the remaining agents, the authors prove that only one welfare distribution in the core satisfies this condition: it is the marginal contribution vector corresponding to the ordering of the agents along the river.

The conditions of *Stability* (as *Core* concept), and *Fairness* (such that no coalition should enjoy more than its *aspiration welfare* where, for aspiration welfare level of an arbitrary coalition of agents, the authors mean the highest welfare these agents could achieve in the absence of the others, yield a unique allocation of welfare. Under this allocation agents receive a payoff equal to their marginal contributions to the coalition composed by their predecessors along the river.

In the model proposed in this article a river flows through some countries or regions or cities (agents) $N = \{1, 2, ..., n\}$. The agents are identified with their location along the river and numbered from upstream to downstream (figure 3).

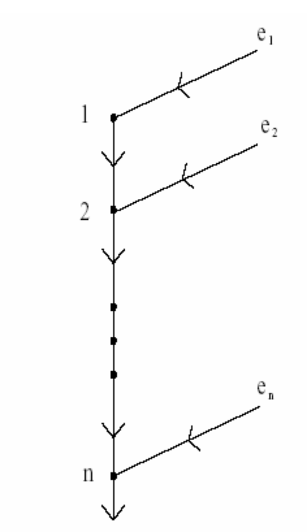


Figure 3: Location of the agents along the river

In this schematic representation we can see that the river increases its volume along its course: the flow e_1 increases from the source (1) and becomes e_2 in (2). Side payments are possible in this model. It is important to note that the water stream e_i can only be consumed by *i*'s followers. The authors prove that the modeled game is convex, so the Core has a simple and well-known structure. They stress the concept of *fairness* and add upper bounds to the agent's welfare, getting a unique solution in the Core, satisfying their requirements for fairness. In the second section of the article, a non-cooperative analysis is discussed.

Van den Brink, Van der Laan and Vasil'ev (2003) investigate a special class of cooperative games–the line-graph games, being cooperative TU-games where the players are linearly ordered. Examples of situations that can be modeled like this are sequencing situations, water distribution situation and political majority voting. The main question in cooperative game models of economic situation is how to allocate the earning of coalitions among the players. They apply the concept of Harsanyi solution to line-graph games. The authors define four properties such that each selects a unique Harsanyi solution from the class of all Harsanyi solutions. One of these solutions is the well-known Shapley value which is widely applied in economic models.

Harsanyi solutions, for a given sharing system, assign to any player a payoff equal to the sum of its corresponding shares in the *Harsanyi dividends*. That is, the concept of Harsanyi solution selects for any game the payoff vector in the Harsanyi set corresponding to the chosen sharing system.

The *line-graph games*, considered in this work, are a special kind of TU-game in which the communication (graph) structure is given by a linear ordering on the set of players. For this class of games the authors define four different properties to be satisfied by a Harsanyi solution.

INTERNATIONAL WATER BASINS

International water resources are rivers, lakes and groundwater resources (some legal frameworks include in the above definition atmospheric and frozen waters also) bordering two or more countries. We dealt with groundwater separately, because of its peculiar features, reflected by the CGT applications in the literature.

As in smaller scale water management situations, each actor can affect the quality and quantity of water available for the other actors, with the difference that the involved players are represented by countries and thus the political and legal context has to be taken into stronger account. Obviously there is still room for a game theoretic approach.

Literature results show that a non-cooperative solution is not the inevitable outcome for the use of an international (and often open-access) water resource, even if an international scale is more difficult to handle.

"*Conflict and Cooperation on Trans-boundary Water Resources*", edited by Just and Netanyahu (1998) is a very complete work about international water management. The book addresses both issues of conflict and cooperation, covering a wide range of possible obstacles to water resource cooperation, such as lack of transparency and asymmetric information, scientific and technological uncertainties, enforcement limitations and upstream/downstream considerations. The analysis focuses on economics, with an extensive use of game theory, but it covers a wide range of disciplines such as political science, environmental sciences, international and national law. In this section we report the first chapter, by Just and Netanyahu, which is a really exhaustive introduction to the problem.

Dufournaud and Harrington (1990, 1991) introduce in their analysis two interesting aspects: time (even if they consider only two time periods) and admissible coalitions. They present a hypothetical example, ‘inspired’ by the cost-allocation problem of Young et al. (1982), and the aim is to implement that study with some temporal aspects.

Becker and Easter wrote three papers about the Great Lakes management. In their 1991 work they analyzed the maximization of benefits in order to get a *characteristic function*, assuming different scenarios characterized by various degrees of cooperation among the states. In (1997), once a diversion scheme for the Great Lakes’ water has been chosen, the focus is on how to apportion the gains and some typical CGT solution concepts are applied (*Core, Nucleolus*, *Shapley value*, *Nash bargaining solution*). In the last paper (1999) they demonstrate that stable cooperative coalitions are possible when a subset of users decides to cooperate: in the example proposed, once a minimum number of users decide to cooperate, the remaining agents have an incentive (interest) to cooperate.

Rogers (1993, 1994), studying the Ganges-Brahmaputra Basin, outlines the applicability of cooperative game theory and *Pareto frontier analyses* to water resources allocation problems, and places his GT model in an accurate geographical and legal framework.

Barrett (1994) tries to answer this question: “Can negotiated treaties ensure that nations which share bodies of water share gains form cooperation?” and concludes: “Often, but not always - and sometimes only partly.”

The necessity of taking into account the political realities surrounding trans-boundary waters is also in Dinar and Wolf (1994). They illustrate the potential of water trading among Middle East countries (Egypt, Israel, the Gaza Strip and the West Bank), accounting for political constraints: a PAS (*Political Accounting System*) is included in the CGT model, in order to take into account the probabilities of formation for the different coalitions.

Luterbacher and Wiegandt (2001) present a cooperative solution that is applicable to the Jordan river basin region: cooperative and non-cooperative strategies are compared, and effects on water consumption are evaluated.

Also in Yaron (2002) the problem of water scarcity is dealt and the starting point of the analysis is a non-cooperative scenario. This paper was reviewed in the section on Groundwater.

Guldmann and Kucukmehmetoglu (2002), whose case study is about Tigris and Euphrates rivers, present a linear programming model allocating water (and maximizing the net aggregate benefits) among agricultural and urban uses of the three riparian countries (Turkey, Syria, and Iraq). Cooperative game theory concepts (Core and Shapley value) are used to identify stable water allocations.

Dufournaud and Harrington (1990) extend cooperative game theory to temporal allocations The approach is illustrated with an example problem involving three riparians and two time periods. Propensities to disrupt are incorporated in the cooperative game in the form that permits the use of linear programming techniques. The results suggest that a considerable range of choices for decisions can be generated by systematic and random investigations near to optimal solutions. In a second paper Dufournaud and Harrington (1991) extend their analysis of the previous model by including linear constraints which satisfy the well known Shapley-value imputation scheme.

In these two papers Dufournaud and Harnington examine the difficulties of managing an international basin, also from the temporal point of view: river basin engineering schemes are long term and, as a consequence, the temporal pattern of costs and benefits must be considered. The framework presented in these works is based on an example of a spatially variant cost-allocation problem presented by Young et al. (1982). Their example is extended to make it a time-variant cost-allocation problem.

Once defined the *Core* of the above mentioned game and an overview on allocation methods found in the literature, the example proposed uses the main concepts of cooperative game theory, the *Propensity to Disrupt*, as defined by Gately (1974), and the notion of *near optimality* discussed in Harrington and Gidely (1985).

In static games with *n* players the possible coalitions are 2^n-1; if we consider *j* time periods the possible coalitions will be 2^{jn}-1. Not all of them make sense and the authors consider only those presumably arising from the concerns specifically articulated by the riparians.

Some inequalities concerning equity and potential for cooperation and disruption are generated and the *Linear Programming Problem* is solved. In the second paper the *Shapley value* is included in the analysis, and it can be done in various ways: The first involves treating each riparian in each time period as a separate player: according to this method, the grand coalition could form in 6! (720) ways. A second way is to develop it for each time period: in this case there would be 5 different '3!' Shapley games in the second period, if the level of cooperation assumed prevails in the first time period. A third way (chosen in the example presented) develops the *Shapley value* over all time periods simultaneously.

Becker and Easter (1991) apply a game theoretic model to the multi dimensional conflict between the USA and Canada over the Great Lakes conflict. In the face of increasing pressure for diversions of water from the Great Lakes, this work considers alternative diversion restrictions and coalition structures for the Great Lakes. The analysis presented here can be used by regulatory bodies and planning agencies to determine which types and limits on diversion restrictions would be desirable. Results also have implications for the desirability of cooperative rather than non-cooperative solutions: unless there is a basin-wide cooperation, most states and provinces ultimately suffer large losses if unilateral and unrestricted diversions occur.

In the past, American states neighboring the Great Lakes have used police power to prevent or regulate interstate water diversions. This power was radically curtailed by the Supreme Court in the early 80's; its ruling found economic purposes insufficient reason to prohibit interstate transfers of water. These rulings, plus requests for additional diversion from the Grate Lakes during drought periods, were the main impetus behind the Great Lakes Charter of 1985 and the Water Resources Development Act of 1986. These two institutional changes created new mechanisms for regulating water diversions from the Great Lakes Basin. The Water Resources Development Act granted the Great Lakes states the right of approval for any federal interbasin diversion of water from the Great Lakes Basin. The Great Lake Charter also established requirements for any state of province to consult and seek consent of all affected states and provinces prior to approving any major new diversion or consumptive use of Great Lakes water (Frerichs and Easter, 1988).

In the Great Lake basin, cooperation can occur on different levels: at the international level United States and Canada may fully cooperate or act competitively; on the national level we can have either cooperation within each country, or there may be full non-cooperation, with each state and province acting alone. The authors consider these three possibilities and develop some models.

For the Region-Wide Cooperation (international level), they consider a *maximization problem*, subject to hydrologic constraints, and solve it. Then they consider the cooperation at the national level, and the non-cooperation between Canada and USA, and in this case we have a maximization problem for both countries. As for the full non-cooperative situation, each state and province act separately and solve its own maximization problem.

Results show the optimal diversion and net benefits for each coalition and diversion restriction. For the fully cooperative case, the paper shows that the unrestricted diversion case brings the largest net benefits among all the situations modeled. (The authors do not consider in this paper the problem of the potential share of those benefits.)

Rogers (1993) reviews the phenomenon of international river basins, and concludes that the sharing of river basins between and among countries is the rule rather than the exception for the major river systems of the world. The growth of the nation state with rivers as agreed-upon boundaries, as cease-fire lines and as natural defensive lines has led to the carving up of most river basins around the world. Two or more countries share more than 200 river basins, accounting for more than 50% of the land area of the Earth.

When population densities were low there was plenty of water for all and major conflicts were avoided. With the rapid population and economic growth experienced in the past few decades, conflicts over use of water are becoming more important. It is expected that in the near future such conflicts will become much more severe. The paper reviews the literature on attempts to analyze river basin conflicts and negotiate solutions. Some rudimentary game models are examined, and some tentative conclusions, based upon various game theory concepts of stability, are applied to the Ganges–Brahmaputra basin. The paper ends with suggestions on how to plan Pareto-Admissible outcomes for international basins.

In a different work (Rogers, 1994) outlines some of the potential solutions to the conflict over the Ganges-Brahmaputra basin water that are shared between India, Nepal and Bangladesh. In particular, the paper emphasizes those Pareto solutions which can be obtained without making any of the participating countries worse-off. While there are no simple solutions to this problem, economics and game theory offer some concepts of what might be "good" solutions.

Rogers examines possible causes of the conflict rising from international water resource management that is the unidirectional externalities in the use of a common resource. The general economic prescription to deal with externalities is to *internalize* them, and the river basin itself is the ideal unit of analysis to achieve this goal. The internationality makes it difficult to agree on these issues, and unless all the riparian countries agree, the basin cannot be developed as a single unit. In this frequent case, in order to internalize the externalities, taxes or fees can be applied but this method requires a strong supra-national institution to impose and collect the taxes. The practical approach dealt with is called *Paretian Environmental Analysis*, first formulated by Dorfman, Jacoby and Thomas (1972): they applied Paretian analysis to upstream-downstream conflicts over the management of water quality.

If we let $NB_i(x)$ be the net benefits accruing to country i, should the resource allocation x be adopted, it is assumed that each country wishes to maximize its net benefit. Formally an allocation x is *Pareto-Admissible* if there isn't any feasible allocation y making $NB_i(y) > NB_i(x)$ for some i with no worse for the other involved players. Baumol's concept of *superfairness* (Baumol, 1986) rests above the Pareto improvement criterion given above, and the concept of 'fair division'.

Game Theory offers a variety of approaches coming from the analysis of the *Core* of an *n*-person cooperative game, based on the idea that there is a set of imputations allowing no coalition to improve the payoffs to its members.

Using the Ganges-Brahmaputra basin model the global maximum $\underset{x \in X}{Max}\left[NB_1(x) + NB_2(x) + NB_3(x) \right]$ is equivalent to the *grand coalition* in game theory terms.

To generate Pareto-Admissible solutions the author followed Dorfman et al. (1972), chosing a set of arbitrary weights W and computed $\underset{x \in X}{Max}\left[W_1 NB_1(x) + W_2 NB_2(x) + W_3 NB_3(x) \right]$.

A wide range of admissible solutions is possible and, according to the way one weights the relative net benefits, they could be used as starting point for arbitration.

The *characteristic function* is constructed and the *Core* of the corresponding game results to be non-empty and "quite small": this should make the task of negotiators easier than in the case of a large range.

Rogers (1991) examines the *Nucleolus* of the game and the *per-capita Nucleolus*, where the per-capita excess (proportional to the number of the players in the coalition) is substituted to the excess used to get the Nucleolus. (Other proportionalities can be constructed on the values of the coalitions.) The *Shapley value* of this game is also calculated and in this paper we find a table with the comparison of the percentages of benefits allocated to the three states through these different allocation schemes.

In a review paper, Barrett (1994) asks the question: Can negotiated treaties ensure that nations which share bodies of water share gains form cooperation? With simplified examples from existing treaties from the Columbia, Indus, and the Rhine Basins he answers that Often, but not always – and sometimes only partly.

Barrett, stresses the issue of interdependence in the management of international water resources introducing a *Prisoners' Dilemma Game* to model the sharing of a common aquifer between two countries, choosing to extract the water at a *High* or a *Low* rate (figure 4).

Figure 4: An aquifer game matrix

	Low	*High*
Low	$(5,5)$	$(2,6)$
High	$(6,2)$	$(3,3)$

If we suppose that the two parties negotiate an agreement specifying that if both choose *High*, one of them should pay an amount equal to 2 to the other party, the agreement can change the *Dominant Strategies* for the players, and of course, the agreement has to be binding.

In the examined case the *externalities* are from both parties, but in other situations the externalities are unidirectional (upstream to downstream, but also vice versa).

The author presents three case studies to provide a perspective on the political economy of international water resource management: the Columbia River Treaty, the Indus Water Treaty and the Convention on the Protection of the Rhine Against Pollution by Chlorides. Then he introduces a theoretical framework of unidirectional externalities.

The *bargaining problem* deals with the sharing of the gains resulting from cooperation (the difference in the aggregate payoff between the non-cooperative and full cooperative outcomes). The full cooperative outcome is the one maximizing the aggregate payoff (in the Prisoners' Dilemma Game presented, the gain is (5 + 5) – (3 + 3) = 4).

There is not a complete compelling theory predicting how the gains will be distributed, even if concerns of equity and reasonableness are widely employed in the analysis of negotiated outcomes.

In a situation of reciprocal externalities, what prevents reciprocal externalities from being entirely internalized is the requirement that such cooperative agreements be self-enforcing (they must include mechanisms which, by themselves, can sustain a cooperative agreement). The point is that, in general, such agreements may be better than the non-cooperative outcome, but may not be able to grant the full cooperative outcome.

Becker and Easter (1997) consider the possibility of 'economically desirable diversions' and how the gains should be allocated among the Great Lakes states and provinces to foster cooperation. The concern about other states diverting water from the Great Lakes has prompted the Great Lakes States and provinces to adopt institutional arrangements that have effectively blocked any new diversions. Since the current arrangements do not allow diversions, important opportunities may be lost in the future. They show that in most cases, new institutional arrangements will be needed before agreements can be reached.

The Great Lakes system is surrounded by two countries, the United States and Canada but within the USA there are eight states governing the lakes, while in Canada there are two provinces. Some states and provinces govern more than one lake, while others border only one lake. In addition, the major hydropower facilities are located downstream from Lake Erie which makes it difficult to develop cooperative solutions. (Becker and Easter, 1997).

Game theory is used to determine how coalitions may be formed to reach cooperative agreements for diversions. Five different lake diversion games are tried involving Lake Ontario, Lake Superior, Lake Erie, Lake Michigan-Huron, and finally, all the lakes together. Diversions from Lake Ontario may offer the best opportunity for cooperation since there are no inter-lake effects.

Once a preferable diversion scheme is selected, the problem of apportioning the gains between the cooperating players still remains, and this is one of the main concerns of this paper.

With the help of game theory, the authors underline that in some cases cooperation may occur without the need of new arrangements, in other cases it is impossible to reach a cooperative solution without new institutional arrangements.

The cooperative game model is developed for Lake Ontario: the *characteristic function* is derived from data and previous analysis conducted by the authors (and reviewed in a previous sections on water allocation).

The game for the Upper Lakes is quite similar to the Lake Ontario's and the Core is always non-empty, except for the Lake Michigan-Huron. It was found that if a diversion is to take place from Lake Michigan-Huron, federal government invention will be required since there is no bargaining solution that will benefit all parties. The *Core* of the game is non-empty. All the results are commented and the authors conclude that in general, more reasonable and equitable solutions were found using the *Nucleolus* rather than the *Shapley value*.

Dinar and Wolf (1997) address possible cooperation in the Western Middle East over the Nile water, showing that there is a need to incorporate more politically related considerations on top of the economic and game theory ones. Their thesis is that cooperation among players requires a realization of economic benefits to all players and a meeting of efficiency requirements through economically driven allocations. Cooperation among political (and sometimes hostile) players may not meet these requirements. Political considerations, usually ignored in economic analyses, can hinder or even block possible arrangements.

The paper proposes a framework that includes both economic and political considerations for evaluating transfers or trades of scarce resources. This method quantifies both the economic payoffs using N-person game theory and the political likelihood of any of the coalitions actually forming, using the PRINCE Political Accounting System. The economic-political approach is applied to a case of potential water transfer in the Western Middle East. Results suggest that incorporating political considerations in the analysis stabilizes the regional solution suggested by economic-related allocations.

A *Political Accounting System* (PAS) to quantitatively and qualitatively predict interactions among players is also used in the political science literature. The PAS assumes that the political impact of players on joint decisions be affected by three factors: issue position, power, and salience. The first element of this system is the *issue position*, expressing the strength of each participant's position for or against each of the issues. A second element is the *power* of a player to influence an issue, the third element is *salience*, i.e. the importance each player attaches to a particular issue.

Two problems may affect the application of the PAS approach: first the measure of values to be included in the PAS is, in many cases, subjective, ordinal, and possibly inconsistent, second this approach does not consider coalitional arrangements among the players.

The authors consider a regional allocation game, where a water resource has to be shared, as well as monetary compensations and exchange of technologies for water, under certain arrangements, among different users in the region.

The *Core*, the *Shapley value* and the *Generalized Shapley value* are considered, and a PAS is included in the model, to calculate political probabilities for the formation of different coalitions. (The *PRINCE* Political Accounting System, developed by Coplin and O'Leary (1974, 1976, 1983) is used in this paper.)

The combined game theory and PAS approach has been applied to a case of water transfer in the Western Middle East. The involved players are Egypt, Israel, the Gaza Strip and the West Bank. The values assigned to the political components of the PAS in this paper are the best quantitative assessment of an elusive quantity. The authors recognize the need to develop more objective measures for each component of political viability.

The results of different allocation schemes for the regional gains are discussed and, to assess the stability of the allocation solutions, the Shapley-Shubik (Shapley and Shubik, 1954) *power index* is applied:

$$\alpha_i = \frac{x_i - v(i)}{\sum_{j \in N} x_i - v(i)}$$

The power index compares the gains of a particular player to the gains of the coalition. A more harmonized power distribution is more likely to yield a stable coalition. The coefficient of variation of the power distribution $S_\alpha = \sigma_\alpha / \overline{\alpha}$ is a measure of stability for each allocation, where σ_α is the variance and $\overline{\alpha}$ is the mean value of α. The allocation resulting from economic considerations only is the most unstable; the game theoretic allocations are far more stable, with the GSVMP being the most stable and the *Shapley value* being the least stable.

Just and Netanyahu (1998) work focuses on the difficulties in forming *grand coalitions*, including all the riparian counties involved in the trans-boundary water basin's management. Their observation of the multilateral agreements stock is that treaties including all riparian countries are an exception rather than a rule (World Bank, 1993).

They examine some guidelines for water apportionment, considering some international treaties, and underline some obstacles to trans-boundary water resource cooperation (asymmetric information, scientific gaps and technical uncertainties, enforcement limitations, sovereignty, conflicting national and international interests, asymmetric country characteristics, upstream-downstream considerations). Using the literature on *coalition formation* they discuss difficulties in forming water agreements in water basins with multiple (three or more) riparian states.

Individual countries form partial coalitions rather than a grand coalition if the game is not *superadditive*. Aumann and Dreze (1974) specify these sources of *non-superadditivity*: inefficiency of the grand coalition, moral hazard problems (for example a country cannot perfectly monitor the clean-up effort invested by polluting riparian countries), and free rider problems.

In contrast to Aumann and Dreze (1974), Owen (1977) and Hart and Kruz (1983), the authors assume that society operates efficiently and that a grand coalition will eventually be formed. The formation of smaller coalitions is considered as a strategic step to bargaining for a larger share of the pie when the grand coalition is formed.

The authors then introduce a hypothetical example of a game in which coalition formation takes place in an environment with economic externalities. First, the example shows how the choice of partial coalitions rather than grand coalitions may be optimal (both when the transaction costs of coordination are considered and when water conservation encounters decreasing returns to scale). Second, the example shows that once the coalition is formed, optimal behavior may allow to have different environmental responsibilities or to receive different allocation opportunities, even when countries are identical, with inequities compensated by side payments.

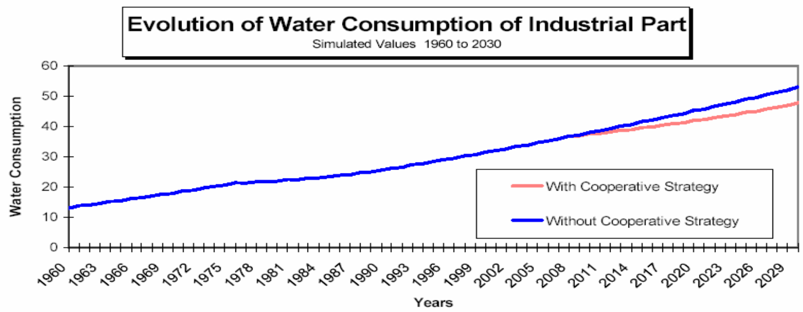
A similar finding is proposed in another paper on Lake Ontario by Becker and Easter (1999). They use game theory to assess the potential for cooperative management. They demonstrate that a noncooperative solution is not the inevitable outcome for the use of an open access water resource. Stable cooperative coalitions are possible when a subset of users decides to cooperate. In their examples, once a minimum number of users decides to cooperate, the remaining noncooperators find that it is in their best interests to cooperate.

A *Prisoners' Dilemma* game is introduced in this paper, to model the case of reciprocal externalities with full cooperation, non-cooperation and partial cooperation. The paper assumes σ to be the portion of users signing an agreement, thus σN is the number of users forming a coalition, while $(1 - \sigma)N$ is the number of free-riders. The equilibrium is calculated basing upon the *Nash equilibrium* for the $(1 - \sigma)N$ players who didn't sign the agreement, once fixed the amount of water diverted by the other players. A coalition is *stable* if: (1) there is no user in the coalition that has an incentive to defect and (2) there is no user outside the coalition who has an incentive to join the coalition.

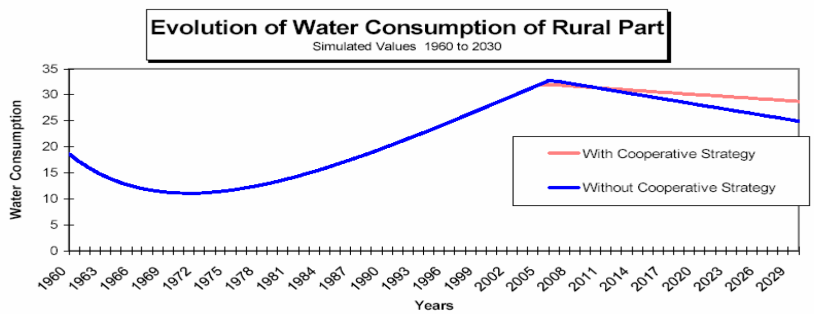
Luterbacher and Weigandt (2001) describe how computer methods can be used to analyze environmental resource problems and evaluate data bases about environmental trends in the Jordan River region. Resource allocation and use depend on both physical and social processes. Conflicts may erupt over overlapping claims to identical resource pools. But because of the complex interactions determining availability and use, solutions to resource conflicts are difficult to elaborate. This study adopts a formulation that focuses on the crucial linkages between the economic, sociocultural, political, and demographic parts of a social system on the one hand, and an important resource sector, water, and its interaction with climatic processes on the other. These linkages are expressed within a dynamic simulation model which has been adapted to the particular case of the Middle East. Samples of the data collection that was undertaken as well as model calibration calculations are given in appendices. The paper explores competition, conflict, and possible cooperation between regions and nations in terms of resource use and allocation, particularly water, and movements of people. The argument is made that cooperative strategies and conflict resolution schemes can be effective in achieving sustainable water management in this region. The underlying theoretical framework is that of game theory, which posits that decision makers are engaged in a process in which their preferences, their possible choices and those of other parties, as well as the mutual effects of choices on each participant, all affect its trajectory and outcome. The advantage of the simulation approach is that it permits the investigation of basic conflict and cooperation situations in terms of their game theoretical structures. The paper presents a cooperative solution that is applicable to the Jordan river basin region.

"A differential game similar to a sequential Prisoners' Dilemma game which leads to a Nash solution in which regions will minimize their water uses (a formal proof which shows that this bargaining mechanism works in the case of two regions is provided). The analysis leads here to a result, which is somewhat similar to the one of the *Folk Theorem* (Fudenberg and Tirole, 1992). However, if the regions are too asymmetric in their access to water resources, as in an upstream downstream relationship, the dynamic bargaining process mentioned above will not work.

Figure 4 below shows that cooperative limitation of water consumption will slow down water demand in the industrial region. As a result, some reserves will be maintained longer and the decrease in water availability in the rural region will be less steep despite increasing drought.



Graph 1



Graph 2

Figure 4: Evolution of water consumption in various sectors with and without cooperation.

Source: Luterbacher and Weigandt (2001)

Guldmann and Kucukmehmetoglu (2002) use a linear programming model that allocates the waters of the Euphrates and Tigris rivers to agricultural and urban uses in the three riparian countries – Turkey, Syria, and Iraq – while maximizing the net aggregate benefits from these activities while accounting for water conveyance costs. Cooperative game theory concepts (core, Shapley value) are used to identify stable water allocations, under which all three countries find it beneficial to cooperate.

Increasing water demand in the Mesopotamia region has brought attention to the transboundary water of Euphrates and Tigris. The paper presents an *optimization model*, which takes into account for the two rivers agricultural use, urban water supply and hydropower plants, and maximizes the aggregate net benefits of the three involved countries. Then CGT is used to allocate water among the different uses and countries in order to make cooperation feasible. Different scenarios are considered, related to future energy prices, agricultural production efficiency, and total water availability. The model is carefully described and different coalitional situations are analyzed, (figure 5).

The total benefit of the *grand coalition* is the maximum aggregate benefit achievable by the three countries. The problem is to allocate this aggregate benefit among the three countries in a way that will persuade them to accept this allocation. *Individual* and *group rationality* have to be met. For individual rationality the authors consider the minimum benefit of a country, taking into account two possibilities:

(i) the country act independently as well as the others, and (ii) the other two countries form a coalition. The *Shapley value* algorithm is described for Iraq.

The modeling approach is applied under each of 27 parameter scenarios, that is, combinations of assumptions regarding energy prices, agricultural productivities, and total water resources. For each scenario the authors find out whether the *Core* exists or not, and, if it does not, then what is the minimum subsidy needed to create a Core. They also check whether the Shapley allocations are in the Core. Six cases have no core, 12 have a single-allocation core, and 9 have a multiple-allocation core (i.e., there is an infinite number of allocations in the core).

Most of the empty-Core cases happen when Iraq is more productive, and when resources are more abundant: in fact these situations allow individual countries to achieve higher benefits on their own (agriculture for Iraq, energy for Turkey), making it more difficult to achieve a sustainable allocation.

When energy is not a factor, all Shapley allocations are in the Core. When it is, none of the Shapley allocations are in core. This occurs because under the assumption of high prices for energy, the Shapley method assigns more benefits to Turkey and Syria, and less to Iraq, and the deriving allocation is out of the Core.

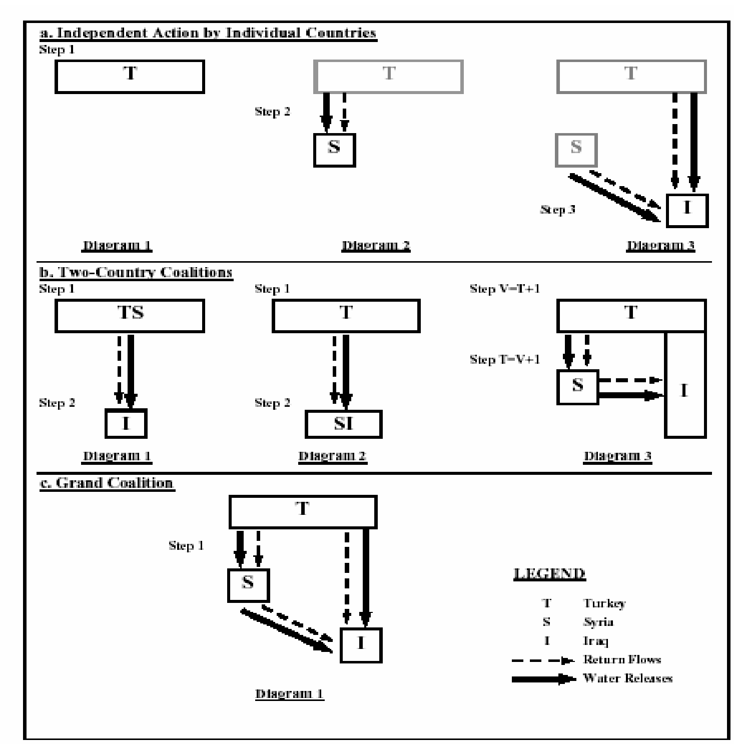


Figure 5: Various coalitional formations and water flows

Source: Guldmann and Kucukmehmetoglu (2002)

CONCLUDING REMARKS

With increased competition over natural resources and environmental amenities, decision makers face strategic decisions in various management and use aspects. Cooperation approaches have been used in many cases, and were proven to be useful under certain conditions. In this review we provided information on various Cooperative Game Theory (CGT) applications to issues of water resources. With an increase in the competition over various water resources, the incidents of disputes have been in the center of allocation agreements. Water conflicts are typical at various levels, including the local (irrigation perimeter, canal, groundwater aquifer, city's treatment plant, etc…), or at regional or transboundary levels (conflicts over allocation issues between sectors such as irrigation and urban, or between states sharing a given river). The paper reviews the cases of various water uses, such as multi-objective water projects, irrigation, groundwater, hydropower, urban water supply, wastewater, and transboundary water disputes.

In addition to providing examples of cooperative solutions to allocation problems, the conclusion from this review suggests that cooperation over scarce water resources is possible under a variety of physical conditions and institutional arrangements. In particular, the various approaches for cost sharing and for allocation of physical water infrastructure and flow can serve as a basis for stable and efficient agreement, such that long-term investments in water projects are profitable and sustainable. The latter point is especially important, given recent developments in water policy in various countries and regional institutions such as the European Union (Water Framework Directive), calling for full cost recovery of investments and operation and maintenance in water projects. The CGT approaches discussed and demonstrated in this paper can provide a solid basis for finding possible and stable cost sharing arrangements.

Several highlights from the sectoral reviews include: (i) The ability to allocate joint costs of multi-purpose water projects (e.g., irrigation, hydropower, flood control components in one project) in such a way that the total cost is covered and at the same time each component is financially and economically justified is a big advantage for planners who need to demonstrate the viability of the entire project and its components. (ii) The urban water supply cost allocation schemes support the viability of projects that serve many customers and are in most countries in jeopardy. CGT demonstrates its ability to account for both efficiency and equity, and as such provides valuable cost sharing rules for policy makers and urban water developers. (iii) Applications to irrigation water cases, although similar to that of urban water, demonstrate the usefulness of NTU and TU situations that are typical to games where players can transfer resources, or the benefits from using the resources, as side payments. A similar situation exists in transboundary water conflict games.

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