Title
Game Theory and Water Resources Critical Review of its Contributions, Progress and Remaining Challenges

Journal
Foundations and Trends® in Microeconomics, 11(1–2)

ISSN
1547-9846

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Publication Date
2015

DOI
10.1561/0700000066

Peer reviewed

Foundations and Trends® in Microeconomics
Vol. 11, Nos. 1–2 (2015) 1–139

DOI: 10.1561/0700000066

Game Theory and Water Resources
Critical Review of its Contributions, Progress and Remaining Challenges

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Dedication

For my eldest grandson Gideon Paz who featured frequently in my work and helped me demonstrate what an effective water policy looks like

Ariel Dinar

For my family, always

Margaret Bush Hogarth

Contents

Abstract

Game Theory (GT), both in its non-cooperative (NCGT) and cooperative (CGT) forms, has been pivotal in its contribution to the analysis of important aspects related to water resources. The 1942 seminal work of Ransmeier on The Tennessee Valley Authority is still considered essential; it continues to inspire many applications related to water allocation decisions. Since Ransmeier, GT models were developed and have been applied to various aspects of water management, such as decisions on cost and benefit allocation in multi-objective multi-use water projects, conflicts and joint management of irrigation projects, management of groundwater aquifers, hydropower facilities, urban water supplies, wastewater treatment plants, and transboundary water disputes.

World water resources face new challenges that suggest a renewed role for GT in water management. Scarcity, growing populations, and massive development have led to increased competition over water resources and subsequent elevated pollution levels. Climate change is expected to unevenly affect the hydrological cycle, leading to increased variability in water supplies across time and space and uncertainty in water allocation decisions. Future investments in water resource projects will be astronomical, needing much more stable rules for cost allocations among participating entities and over time. Levels of water disputes may vary from local to regional, state, and international levels. All of these suggest that while GT models and applications to water resources have advanced over the years, much more is expected.

This monograph will review the main contributions of GT in water resources over the past 70 years. It will compare the set of issues faced by water resources and those which the sector is most likely to face in the coming future. Based on this comparison, a future research agenda and priorities will be proposed. Following the literature's time line with a focus on various methodologies, sectoral applications (such as irrigation, hydropower, environmental water uses, navigation, etc.), and regional issues, we will also identify physical and behavioral features in the water sector that might be conducive to GT (such as scarcity,

externality, uncertainty, and competition-conflict) and some features of intervention (such as the important role for policy, regulation, and incentives), which all affect the likelihood of GT solutions in terms of acceptability and stability.

A. Dinar and M. Hogarth. *Game Theory and Water Resources: Critical Review of its Contributions, Progress and Remaining Challenges*. Foundations and Trends® in Microeconomics, vol. 11, nos. 1–2, pp. 1–139, 2015.

DOI: 10.1561/0700000066.

1

Introduction

The use of Game Theory (GT) to address water resource management issues has been ever increasing since the 1942 seminal application by Ransmeier [1942] to the Tennessee Valley Authority investment project.[1] As is described in Guillermo Owen [1982], the seeds for the development of today's GT were planted in the work by Zermelo [1913] and were advanced to the understanding that economic situations can be modeled as games by Von Neumann and Morgenstern [1944]. GT applications were further developed for logistical purposes during World War II. GT has become one of the basic analytical tools for addressing strategic issues in many fields, including water resources. Following the various applications of GT in water resources over the past half century suggests that it traced a path similar to the state-of-water and water development in the world. This path will be described and analyzed in Section 2 of this monograph. Initially we want to distinguish water resources from other applications of GT.

What makes water an appropriate medium for the application of GT? We will suggest several aspects embedded in water and its interaction with society that make it perfect for GT analysis. First, water

[1] Fisheries will not be included in this review.

is a scarce resource that creates tension between competing users and uses. Conflicts between sectors that need water at different periods during the year, such as irrigation and hydropower are common [Moller, 2005]. In many situations water is characterized as a common pool resource (CPR), opening the door for strategic behavior of the users. Secondly and mostly related, water resources are subject to various types of externalities. One type of externality, the congestion externality, is associated with the CPR nature of water (e.g., groundwater). Another type of externality of water is associated with pollution and is most prominent when upstream–downstream relations prevail. Third, water is associated to a greater extent with uncertainty and asymmetry of information, thus reflecting on the strategic behavior of the agents involved.

Some other reasons for the strategic nature of water can be explained by the fact that not all players ‘behave’ strictly as profit maximizers. Water is seen by various individuals not only as a production resource but also as a source for spiritual needs with existence value. Therefore, ‘optimal’ prescriptions for social arrangements may not be acceptable for various groups in the society. For that reason, most water conflicts involve multi-party multi-objective solutions, and thus the incorporation of strategic behavior considerations, as GT can offer, is essential for socially acceptable arrangements. Such reasons provided the motivation for our work.

The use of GT in water resources by different disciplinary professions such as engineers, international relations experts, economists, and geographers, to name a few, is indeed impressive. The objective of this monograph is to collect the vast literature, catalogue it, and provide present and future practitioners of Game Theory in water resources with a source of information that can be useful for their research. For the sake of conserving space we kept the text explaining GT concepts to a minimum. We assume that readers of this monograph have the basic skills in GT. In places, we provide references to conceptual works for readers who might need help in understanding the relevant GT concepts.

Several databases and Google Scholar were iteratively used to gather literature for this review. Search terms were adjusted according to the vocabularies of each database and the results were analyzed and categorized. An attempt to analyze text using an automated text analyzer failed. For further details, please see Annex 1.

The monograph will be developed as follows. In Section 2, we report the historical trends observed in the accumulation of the GT publications on water between 1942 and 2013. Such trends indicate dynamics of relative importance of sectors and topics over time. They may be connected to global events or crises that took place in the world. Detecting such trends may be useful in explaining the relevance of GT to issues in water around the world. Section 3 describes the developments in Cooperative GT-methodologies to water issues. Cooperative Game Theory (CGT) applications ruled the GT applications during the period 1950–1990. Section 4 reviews the development of Non-Cooperative GT (NCGT) methodologies to various water issues. Then NCGT became more prominent in dealing with water-related issues that involve third parties. Section 5 provides a comprehensive review of GT surveys that have been published in the literature. Section 6 reviews Game Theory applications by sub-sector. We identified 11 sub-sectors and reviewed the applications of GT approaches to each of them. In total, this monograph reviews 289 publications that are directly or indirectly applied to water related issues. We end the monograph in Section 7 with a conclusion and identification of remaining problems to be addressed in the future.

2

Historical Trends

Water-related investments and development projects enjoyed a significant boom after World War II, when the damaged and outdated infrastructure for water supply systems was replaced and expanded, new water supply and irrigation projects had been initiated, and new dams were designed and impounded. GT has played an important role in supporting decisions related to development of water supplies, water treatment, water storage, and water delivery systems. The big infrastructure investment in water projects during the 1940s–1980s has given rise to CGT applications. Once water development projects have been completed, management issues have arisen and had to be addressed, using both NCGT and CGT frameworks (1980s–1990s). The next distinguished period in water resources followed the Rio Declaration in 1992 [United Nations Environment Programme, 1972], which included both the recognition of environmental externalities and that water is an economic good. The Rio platform created the needed setting for the introduction of many applications of GT that addressed water quality aspects, environmental services provided by water, equity issues, and analyses (1990s–2000s). A parallel track that has been extended until 2013 emerged alongside the appearance of global issues such as global public goods, international water conflicts, the impact of climate change on water resources, and the stability of international treaties.

We identified a total of 623 Game Theory publications in water resources.[1] Using the results of Figure 2.1, we were able to identify and classify 294 publications that were found to be relevant for this review. The total trend of these publications indicates a very low trajectory until 1970 and then an exponential growth of 30–80 publications per year. Looking at the 11 categories[2] is even more interesting. We can see a clear and significant increase in several of these categories, while others increased more steadily.

GT work applied to issues in allocation (of water or of joint costs) has increased steadily since the 1950s but then jumped at the beginning of the 1990s as the world recognized the increased scarcity of its water resources, and the needs to better allocate that resource, to build infrastructure to manage it, and then allocate water among the users. Another category of GT work that has shown a significant increase over time is in groundwater. Groundwater (GW) has been for years the orphan resource that frequently escapes public consideration. It is only relatively recently when surface water increased in scarcity that GW got the attention of the world, and of the GT profession. We can see that since the 1980s, groundwater work is increasing. The most fascinating increase in GT applications is detected in the category of international water. New publications in this category were almost unchanged until the 1990s when the numbers sky rocket. In addition to the increased awareness of international and global conflicts, we find (not reported) that the category of international water benefits from GT applications increased by the highest number of disciplines. We found work by economists, international relations experts, political scientists, engineers, and several other disciplines. The category is unique in this respect and different from other categories that employ more than one discipline. The cumulative number of works by year and category is presented in Figure 2.1.

[1]A reference list of GT application works that were not included in our review can be found in Annex 2.

[2]Of the 294 publications, 5 are bankruptcy applications and are not included in separate discussion.

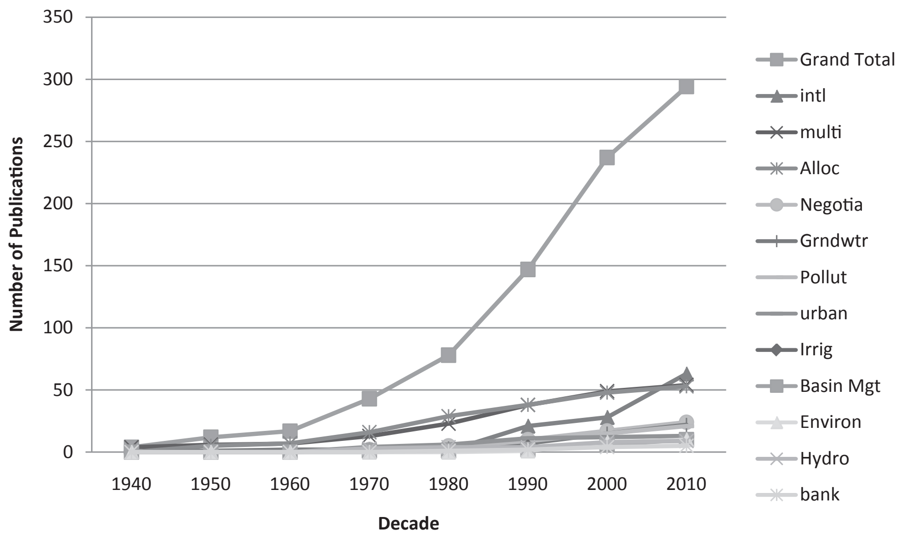

Figure 2.1: Cumulative trends of GT publications by 11 categories, $N = 294$, including five bankruptcy publications.

2.1 Early applications

The work by Ransmeier [1942] was the first to apply CGT principles along with several other methods to allocate the costs of multipurpose water projects among users and uses by the Tennessee Valley Authority (TVA). 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 US Corps of Engineers [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 charged directly to that purpose. The following methods of allocation were considered by the committee" [Parker, 1943]:

- Vendibility theory — acknowledging the fact that a market does not exist where the facilities dealt with can be sold.

- Benefit theory — acknowledging the difficulty of estimating the benefits derived from the projects.

- Use of facilities theory — 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 costs 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, realizing the project outside the joint facility will 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 CGT provided many new tools for the analysis of that kind of problem, 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 Egalitarian Non-Sepearable Cost (ENSC) and with the Seperable Cost Remaining Benefit (SCRB) methods. In a similar way, Young [1994a,b] additionally proposes the TVA 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.

3

Cooperative Game Theory Developments in Water Resources

Game Theory (GT) can be useful in situations when the market mechanism fails. Market mechanisms do not consider strategic interaction among economic agents. Including the strategic interactions among agents could bring more relevant solutions to economic problems of allocation, because it considers the behavioral responses of players and their consequences. GT could be used in these contexts because of its ability to address the economic and social problems of pollution, consumption of resources, and sustainable development.

GT is the study of mathematical modeling of the strategic behavior of decision makers (players), in situations where one player's decisions may affect the other players [Parrachino et al., 2006a]. GT consists of a modeling part and a solution part. Mathematical models of conflicts and of cooperation provide strategic behavioral patterns, and the resulting payoffs to the players are determined according to certain solution concepts. The main types of GT that we consider here are Non-Cooperative Game Theory (NCGT) and Cooperative Game Theory (CGT). The main distinction between the two is that NCGT models situations where players see only their own strategic objectives and thus binding agreements among the players are hard to obtain, while CGT actually is based mainly on agreements to allocate cooperative gains (using Solution Concepts as will be discussed later). Therefore, while NCGT models describe and take into account the strategic interaction among the players, CGT ignores the strategic stages leading to coalition building and focuses on the possible results of the cooperation. In particular, CGT favors solutions that include all possible players (Grand Coalition), and thus most CGT solution concepts refer to the Grand Coalition. An important aspect associated with the solution concepts of CGT is the equitable and fair sharing of the cooperation gains. Young [1994b] notices that equity is something dealt with in everyday life. One can refer to equity in a comprehensive framework, that is, social justice: a proper distribution of resources, welfare, rights, duties, opportunities, or in the narrow framework, for example, how to solve everyday distributive problems. This second case is the one more frequently addressed by GT, which provides the tools to examine equity in a rigorous way, and the problem turns out to be a choice between rules under an axiomatic perspective.

But, as Young underlines, the axiomatic approach has two weaknesses: first, the axioms, reasonable by themselves, may lead to "impossibility theorems"; second, the axiomatic method may result in a solution that is too far from the practical problem which is dealt with: the perceived equity always depends on the particulars of the case. Furthermore, the empirical rules of equity, that one can see applied in real situations, are usually more complex than a single normative principle, and often represent a balance or compromise between competing principles. The term fairness in the literature is sometimes used as a synonym for equity, but some authors often mean something different: their idea of fairness coincides with the acceptability and stability of the cost or benefit apportionment among the players. As was indicated above, the following background is not intended to provide a comprehensive technical basis in GT. Readers who wish to widen their familiarity with the field of GT could refer to Owen [1995], Myerson [1991], Osborne and Rubinstein [1994], Driessen [1988], Peters and Peters [1997], and Aumann and Hart [1992, 1994, 2002].

Due to the nature of water projects (irrigation, wastewater treatment, dams, etc., the cost (or profit) functions of the project (called the joint costs or profits) exhibit strong convexity (sub additively) and thus there is an incentive for joining the grand coalition and enjoying higher cost savings (or profits). In the next section, we provide a menu of several allocation schemes used in the literature related to water. The reader is invited to learn more about the theory behind each of these allocation schemes by visiting the sources provided for each allocation scheme below. While we use cost allocation schemes, the reader can convert them very easily to benefit/profit allocation schemes as well. The examples are taken from Dinar and Howitt (1997).

3.1 Non-GT cost allocation schemes used in GT studies

There are a wide variety of cost allocation schemes for joint operation of facilities proposed in the accounting and engineering literature. Biddle and Steinberg [1985] provide a comprehensive review, from which we use three main types: an engineering approach where the cost allocation is proportional to the physical use of the facility; marginal cost analysis based on economic efficiency principles; and the separable cost remaining benefit (SCRB) principle, where the allocation of the fixed investment is based on an equitable division of the cost. In the following section, the terms “player” and “user” are used interchangeably.

3.1.1 Allocation based on pollution generation

This allocation scheme simply suggests that each user of the joint facility will be charged in proportion to the services the facility provides for this player (e.g., volume of pollution it generates that is treated in the joint facility).

Thus, the cost to user j is:

$$p_j = f^N \cdot \frac{q_j}{\sum_{j \in N} q_j},$$

where p_j is the cost allocated to user j, f^N is cost of the joint facility and q_j is the quantity of pollution generated by user j. This scheme allocates all of the joint cost among all N users.

3.1.2 Allocation based on marginal cost

Allocation on the basis of the marginal cost of the joint facility takes into account the marginal quantities generated by each potential user. Since economies of scale in the joint cost function exist, the revenues generated by this allocation scheme will not cover the total cost. Therefore, an additional procedure is necessary to account for the remaining uncovered costs. Usually this can be done using any proportional rule (such as pollution volume, or volume of production). The formula for this scheme is:

$$b_j = \frac{\partial f^N}{\partial q_j} \cdot \frac{q_j}{\sum_{j \in N} q_j} + \left\{ f^N - \left[\sum_{j \in N} \frac{\partial f^N}{\partial q_j} \cdot f^N \right] \right\} \cdot \frac{q_j}{\sum_{j \in N} q_j}$$

where b_j is the allocation of the joint cost to user j; $\partial f^N / \partial q_j$ is the marginal cost associated with the use of user j; and $f^N - [\sum_{j \in N} \frac{\partial f^N}{\partial q_j} \cdot f^N]$ is the remaining uncovered cost, which is now included in the allocation scheme.

3.1.3 Separable cost remaining benefit (SCRB)

The separable cost of user $j \epsilon N$ is the incremental cost $m_j = f^N - f^{N-\{j\}}$. The alternate cost for j is the cost $f^{\{j\}}$ it bears while acting alone, and the remaining benefit to j (after deducting the separable cost) is $r_j = f^{\{j\}} - m_j$. The SCRB assigns the joint cost according to the following formula [Young, 1985]:

$$k_j = m_j + \frac{r_j}{\sum_{j \in N} r_j} \left\{ f^N - \sum_{j \in N} m_j \right\}$$

In other words, each user pays their separable cost, and the "non-separable costs" $f^N - \sum_{j \in N} m_j$ are then allocated in proportion to the remaining benefits, assuming that all remaining benefits r_j are non-negative for each player.

3.2 Game theory cost allocation solutions

Given the initial conditions of voluntary collective action, and the prior establishment of independent resource management institutions among the users (a region, river basin, etc.), the problem of allocating the joint costs of a joint water facility (joint well, treatment facility, reservoirs, hydropower generation) is modeled as a game among the players. Based on the empirical situation, it can be assumed that institutional regulations facing the players are already in place and that the players agree to consider them. If a player chooses not to cooperate (not to participate in the investment and the operation of a joint facility), it faces a certain outcome resulting from the operation of a private facility or alternative measures needed to meet the regulations. If the players choose to cooperate, they may benefit from economies of scale embodied in the larger capacity of the joint facility with lower average treatment costs compared to the cost in private actions. Some players may cooperate while others may choose not to cooperate, depending on the degree to which they can reduce their cost under cooperation. As a result, the larger the economies of scale, the bigger the incentive for cooperation.

The following is based on Shubik [1982], Shapley [1953], and Young [1985]. Let N be the set of all players in the region, $S(S \subseteq N)$, the set of all feasible coalitions in the game, and $s(s \in S)$ a feasible coalition in the game. The non-cooperative coalitions are $\{j\}$, $j = 1, 2, \ldots, n$, and the grand coalition is $\{N\}$.

Assuming that the players' objective is to minimize their cost, let f^s be the cost of coalition s, and $f^{\{j\}}$ be the cost of the Jth member in non-cooperation. A necessary condition for regional cooperation is that the joint cost will be less than the sum of the individual costs:

$$f^s \leq \sum_{j \in s} f^{\{j\}}, \quad \forall\, s \in S \subseteq N.$$

The joint savings that are allocated among the players are $\sum_{j \in s} f^{\{j\}} - f^s \geq 0$, $\forall\, s \in S \subseteq N$. The above inequality can be interpreted as a cooperative game, with side payments, and can be described in terms of a characteristic function. The value of a characteristic function for any coalition expresses the coalition expenses (or profit, in the case of a benefit game):

$$v(s) = f^s, \quad \forall\, s \in S \subseteq N \quad \text{(see Owen, 1982 for more details).}$$

We will consider four GT allocation schemes that have been widely used in water resources: the Core, the Shapley Value, the Nucleolus, and the Nash–Harsanyi Allocation.

3.2.1 The core

The Core of an *n player*-cooperative game in the characteristic function form is a set of game allocation gains that is not dominated by any other allocation set. The Core provides a locus for the maximum (or minimum in terms of cost) allocation each player may request. In this respect, it is an overall solution for several allocation schemes that are contained within the Core. The Core fulfills requirements for individual and group rationality, and for joint efficiency [Shubik, 1982].

CGT is conducted under the assumption that the players in the game are economically rational. This means that the decision of each player to join a given coalition is voluntary, and is based on the minimal cost they bear by joining that coalition (in a benefit game it is the incremental benefit they gain). Let ω_j be player j's Core allocation of the cost from the game. The Core equations (for the case of a cost allocation game) are:

$$\omega_j \leq v(\{j\}), \qquad \forall\, j \in N,$$

$$\sum_{j \in s} \omega_j \leq v(s), \qquad \forall\, s \in S,$$

$$\sum_{j \in N} \omega_j = v(N).$$

The first inequality in the Core fulfills the conditions for individual rationality — that is the cooperative solution for each player is preferred to the non-cooperation case. The second inequality fulfills the group rationality conditions — that the cooperative allocation to any combination of players is preferred to any allocation in any sub-coalition they can establish. And the third inequality fulfills the efficiency condition — that the joint cost will be fully covered by the grand coalition participants. The system of these three inequalities has more than one allocation solution. A method of calculating the extreme points of the Core [Shapley, 1971] provides the incremental contributions of each player when joining any existing coalition, and assigns these contributions to that player. Thus, having a non-empty Core for a cooperative game provides the necessary condition for a solution that will be acceptable to the players.

3.2.2 The nucleolus

The Nucleolus [Schmeidler, 1969] is a single point solution that always exists (if the Core is non-empty) and minimizes the dissatisfaction of the most dissatisfied coalition. To obtain the Nucleolus, we define the ε-core of the game v to be the set of allocations that would be in the Core if each coalition were given a subsidy at the level of ε. By varying ε one finds the smallest non-empty ε-core (called the least Core). The least Core is the intersection of all ε-cores. The least Core for a cost allocation game satisfies:

$$
\begin{aligned}
&\text{Min } \varepsilon \\
&\text{subject to} \\
&\sum_{j \in s} \omega_j \leq v(s) + \varepsilon, \quad \forall\, s \subseteq S, \\
&\sum_{j \in N} \omega_j = v(N), \\
&\varepsilon \lesseqgtr 0.
\end{aligned}
$$

The solution to the minimization problem above may provide the Nucleolus (as a single solution) but it may also provide several individual cost allocations ω_j for the same value of ε for each coalition s. In this case, we define the excess function $e(\varepsilon, s)$ for each s (that measures how much less it costs a coalition to act alone) and in a lexicographical process [Schmeidler, 1969] obtain the Nucleolus, for which the value of the smallest excess $e(\varepsilon,\ s)$ is as large as possible.

The interpretation of ε is interesting. It can be used as a tax or a subsidy to change the size of the Core. If the Core is empty, then ε ($\varepsilon < 0$) is an “organizational fee” for the players in sub-coalitions, causing them to prefer the grand coalition. If the Core is too big, ε might reduce it ($\varepsilon > 0$) by subsidizing sub-coalitions. The Nucleolus is always in the Core if it exists.

3.2.3 The Shapley Value

The Shapley Value [Shapley, 1953] scheme allocates θ_j to each player based on the weighted average of their contributions to all possible coalitions and sequences. In the calculation of the Shapley Value, an equal probability is assigned to the formation of any coalition of the same size, assuming all possible sequences of formation.

The Shapley value is calculated as:

$$\theta_j = \sum_{s \subseteq S\, j \in s} \frac{(n - |s|)!(|s| - 1)!}{n!}[v(s) - v(s - \{j\})], \quad \forall\, j \in N,$$

where n is the number of players in the game, and $|s|$ is the number of members in coalition s.

3.2.4 The Nash–Harsanyi (N–H) solution

The N–H Solution [Harsanyi, 1959] to an n-person bargaining game is a modification to the 2-player Nash Solution [Nash, 1953]. This solution concept maximizes the product of the grand coalition members' additional utilities (income, or savings) from cooperation compared to the non-cooperation case, subject to Core conditions, by equating the utility gains of all players. The N–H Solution satisfies the Nash axioms [Nash, 1953]; it is unique and it is contained in the Core (if it exists). The solution might provide unfair allocations if there are big utility differences between the players (e.g., very rich player and very poor player).

The N–H, h_j, is calculated as:

$$\max \prod_{j \in N} (f^{(j)} - h_j)$$

subject to the Core conditions:

$$h_j \le f^j, \qquad \forall\, j \in N,$$

$$\sum_{j \in s} h_j \le f^s, \qquad \forall\, s \subseteq S,$$

$$\sum_{j \in N} h_j = f^N,$$

where h_j is the N–H allocation that satisfies efficiency and individual rationality conditions.

The fulfillment of the Core conditions for an allocation scheme is a necessary condition for its acceptability by the players. Thus, solutions not included in the Core are also not stable. Although an allocation scheme may fulfill the Core requirements for the regional game, it still may not be accepted by some players that might view it as relatively unfair compared to another allocation. Allocations which are viewed as unfair by some players are less stable. Some players might threaten to leave the grand coalition and form sub-coalitions because of their critical position in the grand coalition. The stability of any solution is important given the existence of fixed investments, and a more stable solution might be preferred even if it is harder to implement.

We do not discuss coalitional stability here. The reader is referred for more reading to Shapley and Shubik [1954] and Loehman et al. [1979] who used a measure of power in voting games. This power index is also used in Williams [1988]. Another measure of stability was introduced by Gately [1974] as the "propensity to disrupt" the grand coalition and was modified and applied (for $N > 3$) by Straffin and Heaney [1981] to the case of the Tennessee Valley.

3.3 Developments in cooperative game theory solutions

Several developments were reported in the literature, which have implications for the application of CGT to water. Loehman and Whinston [1971] introduced the Generalized Shapley Value, which is a very relevant modification to the Shapley Value.

3.3.1 The generalized Shapley Value

The Shapley Value assumes equal probability for the formation of any coalition of the same size, which is theoretically possible, and also considers all the possible sequences of formation. Loehman and Whinston [1976] criticized this assumption on the basis of the Shapley Value and they proposed the Generalized Shapley Value. The Generalized Shapley Value differs from the Shapley Value in two aspects: (1) it refers only to coalitions that are practically possible, rather than possible from a theoretical combinatorial point of view, and (2) the probability of a coalition occurrence depends on the logical sequence of its formation. The Generalized Shapley Value assigns, in a similar manner, to each player the weighted average of its contributions to all realistically formed coalitions:

$$\vartheta_j = \sum_{\substack{s \subseteq S \\ j \in S}} P(s, s - \{j\})[v(s) - v(s - \{j\})], \quad \forall j \in N$$

where $P(s, s - \{j\}) = P(s|s - \{j\}) \cdot P(s - \{j\})$.
and $P(s) = \sum_{j \in s} P(s, s - \{j\})$.

$P(\cdot)$ is a conditional probability, which is interpreted as the probability of a certain player, j, joining a certain coalition, $s - \{j\}$, given the structure of the coalition that existed without that player. Conditional probabilities are determined from "decision trees," which result from the coalition formation process. An example can be found in Loehman et al. [1979]. Calculating the Generalized Shapley Value is straightforward, and follows a similar procedure as the Shapley Value.

3.3.2 Set solution concepts

To conclude this section, we will briefly mention several set solution concepts in addition to the Core. These solution concepts were applied to water resource allocation issues. Such solutions include the Bargaining Set [Aumann and Maschler, 1964], the Stable Set von Neumann–Morgenstern Solution [1944], the Kernel [Davis and Maschler, 1965], and the Least Core. More on these can be found in Aumann and Dreze [1974] and in Parrachino et al. [2006a].

3.3.3 Dealing with externalities: the γ-core

Management of water resources is at times associated with negative externalities, such as congestion in the use of Common Pool Resources (groundwater), or such as pollution in the upstream–downstream geography of transboundary water bodies (such as international water).

Several concepts have been developed to deal with such externalities within the framework of cooperative games. We will mention one that has been used in the work cited in this paper.

The γ-Core developed by Chander and Tulkens (1992, 1997, 2006 and the references there in). was applied in many works that deal with international environmental agreements on pollution (mainly global climate change agreements). In our paper, the γ-Core was used in the work by Fernandez [2002, 2005, 2009], where she applied it to the transboundary water pollution problem in the Tijuana River, shared by the United States (US) and Mexico.

The γ-Core for pollution games consists of allocations (treaties in the transboundary context) that specify a profile of allowed emissions for each player, that are Pareto efficient at the global scale, and transfers (positive or negative) amongst the parties, that cover the total cost of abatement for each of them, and are financed by contributions from each based on their relative (marginal) environmental damage costs. The γ-Core is based on the assumption that in the case of defection by some subset S of parties, the other parties will abandon any form of cooperation and act to the best of their interest as singletons in the face of S.

The γ-Core is basically the result of transfers of compensations received and paid by the various members of the grand coalition in the game, and can be formalized by the following equation [Chander and Tulkens, 2006]:

$$T_i = -[g_i(p_i^*) - g_i(\bar{p}_i)] + \frac{\pi_i'^*}{\sum_{j\in N} \pi_i'^*} \left[\sum_{j\in N} g_j(p_j^*) - \sum_{j\in N} g_j(\bar{p}_j) \right],$$

where p_i is pollution of player i; g_i is GDP and π_i is total damage caused to player i by the aggregate emission (externality) $\sum p_i$.

4

Non-Cooperative Game Theory and Other Related Developments in Water Resources

Non-Cooperative Game Theory (NCGT) concepts have been applied to various water resources issues. Non-Cooperation Games include situations where interdependencies exist among players, which affect each other. Players maximize their own utility irrespective of the utility of other players, either taking into account their opponents' decisions or ignoring their opponents' decisions (the Prisoner Dilemma Games). Non-Cooperative Games can be presented in extensive or strategic forms. Games in extensive form provide a detailed documentation of a player's moves and the ultimate payoff and the end of the game. Games in strategic forms are a 'folded' version of the moves into a matrix form where each cell represents the outcome payoff to each player from each particular strategy [Shubik, 1982, Owen, 1995].

4.1 Games in strategic form

Situations where individual players do not consider the overall benefits of the riparians to a river basin, or users of the same aquifer, or neighbors to the same lake, are quite common in the field of water resources. The geography of the location of the players along the water body is also important in such cases (the case of unidirectional externality) and affects whether or not cooperative or non-cooperative arrangements are likely. This 'structure of the problem' affects the nature of the game and will dictate the type of strategic form of the game.

Dombrowsky [2007] provides quite a large set of examples of 2×2 games from various international river basins that are characterized by different problem structures and demonstrate how various types of games (Pure Coordination; Assurance; Prisoner's Dilemma; Chicken, Battle of the Sexes; Deadlock; Constant Sum, and Rambo) apply. We should also mention that in addition to the problem structure mentioned earlier, one has to consider whether the game is a one-shot game or a repeated game. We will review only a subset of the examples provided by Dombrowsky [2007].

The first example is of the Mountain Aquifer that is shared by the Israelis and Palestinians. The Israelis use the most water resources at present, and the Palestinians request to have their water rights as well. In a Chicken game structure each player prefers not to yield to the other, and the worst possible outcome occurs when both players do not yield. At present it seems that the Israelis have moved first and allocated most water resources to their needs. They discount the Palestinians' requests to allocate to them more water resources and do not suggest they joint manage the water in the aquifer. The author argues that since the asymmetry between the two parties at present is so significant, the game structure of Prisoner's Dilemma is not appropriate and rather a Chicken game structure prevails.

The second example is from a game of wastewater treatment in order to reduce pollution by two different players (the situation could also be relevant for pollution reduction in general). The strategies faced by each player are to pollute or to abate. Abatement is done jointly because it is more cost effective. Abatement is associated with major economies of scale. Because of the economies of scale this is an Assurance Game, in which the two players are aware of the significant gains they may realize from working together. Such situations exist in the management of the Great Lakes between Canada and the US, several lakes in Europe, Lake Victoria, and many other lakes.

The last example deals with provision of retention areas for flood control at border rivers that are shared by two countries. This is an example of a reciprocal externality that affects mainly the downstream country. Strategies by each player could be to provide or not to provide a retention area on their territory to benefit both players, but mainly the lower riparian state. This is a Prisoner's Dilemma game that is observed in Europe in the Oder Basin that is shared by the Czech Republic and Poland, or by Poland and Germany.

4.2 Bankruptcy games

Bankruptcy Games are games that are similar to a situation where a group of creditors face a total debt that exceeds the total financial assets to be credited among the creditors. In water resources, this is characterized by a situation in which a resource is available at a level below the demands of all users. This is very common in cases where water had common pool resource characters with multiple users leading to overuse, congestion, pollution, destruction, and behavior based on individual rationality rather than group rationality. Bankruptcy arrangements can either be achieved via cooperation among the users, or via external interventions by the regulator, or an agreed-upon mediator. General characteristics of bankruptcy games are included in Gura and Maschler [2008].

In cases where total resources are below the aggregate demand the expected exploitation of each user should be reduced by some amount, which can be calculated using different bankruptcy methods available in the literature [Curiel et al., 1987, Dagan and Volij, 1993, Kampas and White, 2003, Madani and Dinar, 2013].

One possible allocation is by using the proportional rule, by which the regulator may reduce each user's expected exploitation of the resource by a given share. The entire reduction would then meet the level of resource bankruptcy. Another approach could be to use the constrained equal award (CEA) rule, which intends to enforce justice by satisfying the poor users, who may lose more from share reduction, before satisfying the rich beneficiaries, who may not bear significant losses from share reduction due to their relatively high wealth level.

5

Reviews/Surveys

Several reviews have been published in the past 30 years, many of which focus on practical applications of GT. To acknowledge the review nature of these publications they will be surveyed here. The earliest review that we were able to identify is by Bogardi and Szidarovszky [1976]. The authors survey the possible application of Oligopoly Game Theory to water issues such as water quality management, multipurpose water management, environmental protection, and irrigation system management. While the principles for Oligopoly Games suggest that players do not have dominant or dominated strategies, in the four areas of application it is not always easy to identify those that follow such requirements. This is especially true given the geographical nature of the water system leading to water polluters and victims, or power embedded in the position of the players.

Sheehan and Kogiku [1981] further review the CGT literature in water resources available by the late 1970s. They use simplified but realistic scenarios to illustrate the concepts of fair allocation of joint costs and benefits along with some of the pitfalls such as the Prisoner Dilemma Situation in the case of no cooperation. They suggest and demonstrate the use of 5 rules for allocation of joint costs or benefits in various situations, using the available literature: (1) Egalitarian division of incremental gains among the participants (Nash Allocation); (2) division by the ratio of costs each player would have paid under the status quo (noncooperation); (3) distribution of benefits which is most likely to result from a stable coalition, meaning a distribution which equalizes the "propensity to disrupt" of all the participants; (4) Shapley Value; and (5) distribution based on the "power" of the participants, based on the "kernel" solution of the game (See Section 3.2).

Game theory applied to transboundary pollution of various resources, including water, has been reviewed by Missfeldt [1999]. The paper reviews the various issues facing transboundary polluters and how different types of transboundary pollution have been approached, using static and dynamic game theoretic solution concepts. One conclusion reached is that while full cooperation among the polluter countries leads to economically optimal outcomes, it is difficult to achieve, mainly due to differences in abatement costs across the countries and incentives to free-ride. Mechanisms such as side payment, coordination and information sharing, sanctioning, and self-enforcement are reviewed.

Parrachino et al. [2006b] review applications of CGT to water resources in multi-objective water projects, irrigation, groundwater, hydropower, urban water supply, wastewater, and transboundary water disputes. While providing the rationale to, and demonstrating the difficulties of the application of CGT models, the review also talks about the stability of the cooperative solutions. Among several stability measures of the cooperative solutions, the authors describe the Shubik–Shapley Power Index [Shapley and Shubik, 1954], a discussion of which can be found also in Section 3.2. A review of the work on application of CGT to natural and environmental resources other than water can be found in [Zara et al., 2006]. While not focusing on water, the CGT solution concepts reviewed are applicable to various water resources, as they are reviewed in this monograph.

A review and comparison of various CGT allocation schemes that have been discussed above for urban water supply and sanitation projects, is presented in Loehman [1995].

An illustration of various NCRG games (Prisoner's Dilemma, Chicken, Assurance, and Dynamic Games) is reviewed in Madani

[2010] with focus on water resources conflicts. Using a simple 2-person game, the author demonstrates the relevance of the various games to issues associated with transboundary water allocation, water pollution, water resource development, and groundwater management. While the NCGT principles are explained with a very simple 2×2 matrix, the consequences of Nash Equilibrium and the potential for cooperation are well demonstrated.

Finally, for this section, we introduce the review by Madani and Hipel [2011]. They review several stability definitions that are associated with NCGT and applied to water resources. The stability definitions reflect the nature of agents involved in the game (planning horizon, risk aversion, and level of asymmetry of information). The combination between the characteristics of the agents and the problem of the water resources' management guides the selection of the stability measure of the game solutions: nash stability, general metarationality, symmetric metarationality, sequential stability, limited move stability, and non-myopic stability (all are illustrated in Section 3.2).

6

Sectoral Applications

Over the years, GT applications have been developed for several water sectors. We were able to identify 11 sector typologies that mark an important contribution to the literature. They include: urban water supply and sanitation, irrigation, hydro-electric power, water pollution control, groundwater, allocation issues, international/transboundary water, water conflict and negotiations, water and ecological systems, watershed management and regulation/river basin planning, and multipurpose water projects. Each of these sub-sectors may have some unique features that are reflected in the particular way the GT approaches were applied to them. The reader may find that some of the material included in one sector typology could have been placed in another sector typology. In that respect, our decision for inclusion of material in a given sector typology reflects our best assessment, but we indicate the synergy where relevant.

6.1 Urban water supply and sanitation

This subsection represents a major contribution to the literature in the early stages of application of CGT approaches to water supply and

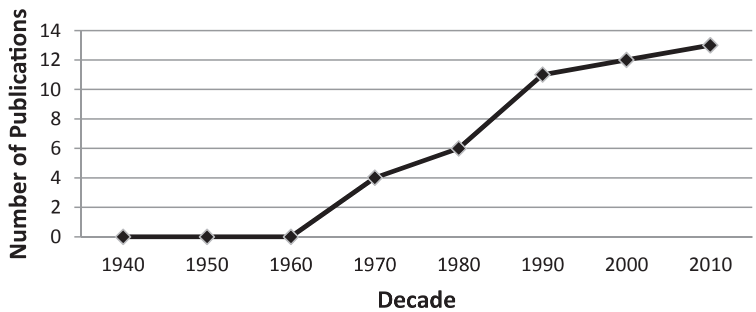

Figure 6.1: Annual GT publications, urban, $N = 13$.

sanitation projects, starting in early 1970s. Most of the works in this section address the cost and/or benefit allocations of joint projects in the urban sector. Some works also address fairness considerations and the stability of the allocation arrangements.

The majority of the studies reviewed deal with the acceptability and stability of joint water projects, either wastewater treatment facilities, or water supply projects. Given the economy of scale nature of water supply and sanitation projects, the players involved are usually cities that consider whether or not to cooperate in building a water supply or treatment facility. The usual question is what should be the pricing scheme that will allocate the costs and/or benefits among the players involved? Some works also involve a government for possible subsidies and regulations, and the environment as a possible victim of externalities (pollution) that may be the result of the project, or avoided if the project will be initiated. The annual number of published works in this category is presented in Figure 6.1.

Giglio and Wrightington [1971] address a very relevant issue even for today's water project situations: the question of regional vs. subregional facilities to treat water. The regional setting means economies of scale and the possibility of reducing the costs of treating wastewater (for example) for each urban center. If this is correct then the grand coalition is preferable. However, it might be possible that the treatment cost function has convexity properties such that it will attract a given urban center to join a sub-group (sub-coalition) instead of the grand coalition. The paper demonstrates, using n-person CGT and linear programing, how such a situation can be addressed. In a subsequent paper, Giglio and Wrightington [1972] examine three methods in use for allocation of costs of joint wastewater treatment facilities among users: (1) cost sharing based on the measure of pollution; (2) cost sharing based on single plant costs with a rebate proportional to the measure of pollution; and (3) cost sharing based on the Separable Costs Remaining Benefit (SCRB) method. Main findings are that often these three methods do not provide allocations that satisfy all the players, leading to decisions to not join the grand coalition (regional plan), ending in a less-than-optimal regional setting. In comparison to the above three methods, the authors introduce two cooperative n-person, non-zero sum games possessing a Core, with two nuances: (4) where the authority is not a player, and (5) when the authority is a player with interests of maximizing taxes. The CGT models show higher satisfaction on the part of the various players.

In a similar manner, Dickinson and Heaney [1982] compare several ad hoc methods that are used in the empirical literature to allocate the costs of a water resource project among participants and/or purposes. As was found in Giglio and Wrightington (1971, 1972), these methods lead to unfair allocation of the joint costs. The paper compares criteria used for fairness measurement to those used in cooperative n-person game theory approaches. Findings suggest that the minimum costs remaining savings (MCRS) method is proposed as an improved method of financial analysis. The MCRS method can be viewed as a generalization of the presently used SCRB method that was discussed in Section 3.1. Similar ideas are expressed in Heaney and Burke III [1976]; and in Lippai and Heaney [2000] who present an efficient and equitable method for determination of fees for urban water systems in a fair manner. Based on n-person CGT they introduce mechanisms for cost allocation by urban zones, user classes, and/or demand types in a small urban water system.

More work on similar applications of cost allocations using CGT approaches can be found in Holler and Li [1996], and Lejano and Davos [1995], who introduce the Normalized Nucleolus and compare allocation results with those obtained by the Nucleolus and the Shapley Value, and Lejano and Davos [1999].

A classical work on investment in water supply system and allocation of its joint costs in Sweden is provided in Young et al. [1980, 1982]. The importance of these two works is that they estimate the joint cost function of the project from real world available data [see also Dinar and Howitt, 1997, in Section 6.9] and incorporate this information into the characteristic function of the possible coalitions involved. They compare several allocation mechanisms of the joint costs on the basis of certain commonsense principles of equity (the Separable Costs Remaining Benefits — SCRB, the Shapley Value, and Variants of the Core). Advantages and disadvantages of the methods in practice are examined on the basis of practical project implementation considerations. While the authors do not provide recommendations regarding prioritization among the allocation schemes, they conclude that the SCRB may be one of the worst.

Another application focusing on the Shapley Value and the Generalized Shapley Value (see Section 3.2) is reported in Loehman et al. [1979]. An n-person Cooperative Game is developed for a region with eight polluters of the Meramec River Basin in Missouri that have to meet pollution standards and reduce their emissions via a joint treatment facility. The contribution of this work is not only in the introduction of the Generalized Shapley Value, but also in an unusual involvement of the 'real' players in the evaluation process — after the suggested cost allocations of the joint facility have been calculated they were shared with the players for feedback. The main feedback was that the different players in the Meramec River Basin in Missouri felt that the Shapley and the Generalized Shapley Values are too complicated to understand, and that the concept of income transfer among the players was hard to accept [for a broader discussion and comparison to other allocation schemes see Loehman, 1995].

Dinar et al. [1986] address the somewhat new approach, at that time, of reuse of treated municipal wastewater for irrigation (a wastewater market), rather than its disposal to the dry streams or ocean, in a regional context. Optimization of the size of the treatment facility, level of treatment, and location constitute the basis for the regional characteristic function. Allocation of the joint costs and benefits were calculated, using both marginal cost pricing methods and CGT methods (Core, Nucleolus, Shapley Value, and Generalized Shapley Value). In addition to calculating the various allocations by each method to each player (the city that produces the wastes, and the three farms that are the potential users of the treated wastewater), the authors compare the fairness, reasonableness, and acceptability to the players, which is the basis for the stability of the proposed allocation solution.

To conclude the review of the urban and sanitation applications, Amit and Ramachandran [2010] introduce an NCGT principal–agent contract approach in a two-period game to reach a stable and acceptable demand management plan that will escape the market failure problem while achieving fair charges for users. In public utilities, under supply constraints, fairness considerations lead to a market failure. The contract between the principal and the agents is designed as an extensive form mechanism using Subgame Perfect Nash Equilibrium (SPNE) as the solution concept. The contract is fair and economically efficient: in case of deviation by the agent, the gain to the agent and the loss to the principal are small.

6.2 Irrigation

The irrigation sector represents a common pool resource management situation. The common pool could be an aquifer or a reservoir shared by several irrigators. Most applications of GT to the irrigation sector address issues in cost sharing of a joint irrigation water system. As such there are CGT applications.

Works in this category can be divided into two groups. The first group of works includes studies that analyze the interaction between irrigators in the irrigation project. Questions addressed include: pricing of the water and services provided by the project to the different irrigators, and contributions of the individual irrigators to the public good nature of the water infrastructure. The second group of works includes studies that look at the irrigation sector as a player that competes with

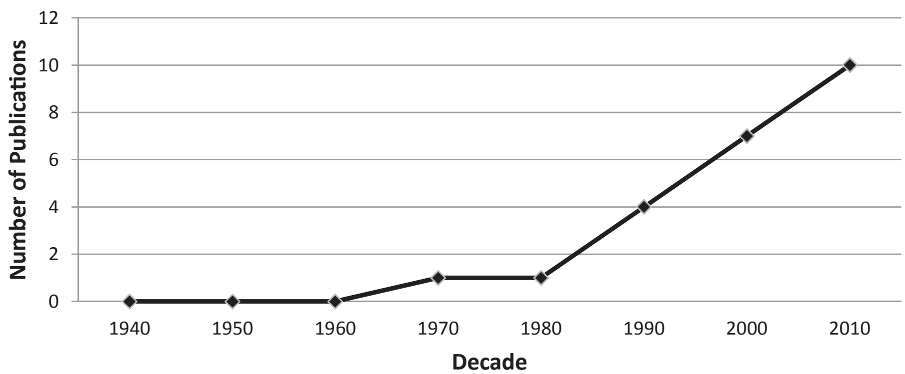

Figure 6.2: Annual GT publications, irrigation, $N = 10$.

other sectors over scarce water. In this group of works, the opportunity costs or benefits from using scarce water by the irrigation sector are incorporated into the analysis. The annual number of published works in this category is presented in Figure 6.2.

A relatively early application by Sawaragi et al. [1978] attempted to analyze how Japanese irrigators govern their common pool resource (CPR) irrigation facilities. Opposite to early beliefs, the results suggest that State and market approaches ignore the endogenous institutions that CPR users develop and prefer external regulations, such as government coercion to help rational, self-interested users maximize their group benefits or privatize their resources. The irrigators are farsightedly rational in collective action situations and the government does not need to apply coercion to make the rational, self-interested irrigators achieve their common interests. The results of this early study are similar to those of Madani and Dinar [2012a,b]. Similar findings were also suggested, based on the series of studies on various CPRs that were summarized in Ostrom et al. [1994] finding that self-governance of CPR does not lead to the tragedy of the commons.

In a series of papers Aadland and Kolpin [1998, 2004a,b] examine various aspects of irrigation project cost sharing arrangements. In their 1998 paper, Aadland and Koplin show that the variations of serial and average cost-sharing mechanisms can be characterized as unique solutions to equity-constrained welfare maximization problems. In their 2004a,b papers they find that the shared irrigation costs that are adopted reflect the extent to which the structural environment affects the costs and the benefits of the irrigators along the canal. The innovation in the model suggested by Aadland and Kolpin [1998, 2004a] is the use of the variable “Center of Gravity” which measures the impact of the degree of heterogeneity between head and tail farmers’ demands for water on a given ditch. These differences will affect the selection of the allocation rule:

$$\mathrm{CoG}_j^0 = \frac{\sum_{i=1}^{m_j}((d_{ij} - \min_i(d_{ij}))\mathrm{acre}_{ij})}{(\max_i(d_{ij}) - \min_i(d_{ij}))\sum_{i=1}^{m_j}\mathrm{acre}_{ij}}$$

where d_{ij} is the linear distance from the headgate to the ith private point of diversion, acre_{ij} is the number of irrigated acres associated with the ith private point of diversion, and m_j is the total number of fields. CoG_j^0 is bounded between 0 and 1, with values close to 0 indicating a concentration of irrigated acres near the head. A CoG_j^0 closer to 1 indicates that tail-end users are closer to the average in a relative sense, leading to consideration of excess demand protection to be less important in the allocation rule. This type of consideration, based on distribution of the irrigators, has equity and stability.

A different approach to the same water management problem has been applied by Bardhan [1993] in order to understand the success and failure of local cooperative institutions, using evidence from fieldwork and CGT applied to evolutionary biology and economics. Some of the most interesting findings from Bardhan’s study is that the variation of some parameters across the participants have a high impact on the stability of the group rules of operation. For example, a low variance of the average annual farm income level is associated with a high level of rule conformance and good maintenance. Also, the smaller the variation in farm size among the farmers, the more likely they are to establish water-user organizations.

A different approach is undertaken in two separate studies by Getirana et al. [2008] and Getirana and de Fatima Malta [2010]. Both studies apply GT approaches to conflict among irrigators among the Coqueiros Canal water users, located in the Campos dos Goytacazes municipality, in the northern region of the State of Rio de Janeiro, and a canal in Rio de Janeiro State in southeastern Brazil. A graph model of a NCG was developed for conflict resolution. The authors developed six scenarios pertaining to the decision makers, and their options and strategies. Then they identified two possible roles for the managing institution: first, that the conflict resolution managing institution takes into account that it has no explicit preferences for any of the outcomes, and the second one is such that the managing institution shows explicit preferences for the scenarios which provide more income taxes. In both the cases, the results suggest a solution to the conflict among the irrigators, with the demand for irrigation water affecting the priorities in the solution.

6.3 Hydropower generation and reservoir operation

GT applications in the hydropower sector can address a range of issues, including market allocation among operators of different types of dam technologies, operation of multipurpose dams, reservoir operation in deficit water storage periods due to drought and high scarcity, and negotiations in the process of institutional reforms of the regulatory framework of hydropower generation. GT applications can also include market simulation (quantities and prices) in the case of a static (Cournot) model and a dynamic (Cournot–Nash) model, and cooperation and its stability in the case of multi-agent investment in hydropower generation. Several works also address the negative externalities between hydropower production and the environment. The annual number of published works in this category is presented in Figure 6.3.

Dakhlaoui [2008] analyzes infinite discrete-time games between hydraulic and thermal power operators in the wholesale electricity market, using the Cournot Closed-Loop game and the Stackelberg Closed-Loop game. There are two energy sources: hydropower and thermal. Decisions by the hydraulic operator are subject to the stochastic dynamic constraint on the water stored in the dam. In contrast, the thermal plant is operated with quadratic cost function, with respect

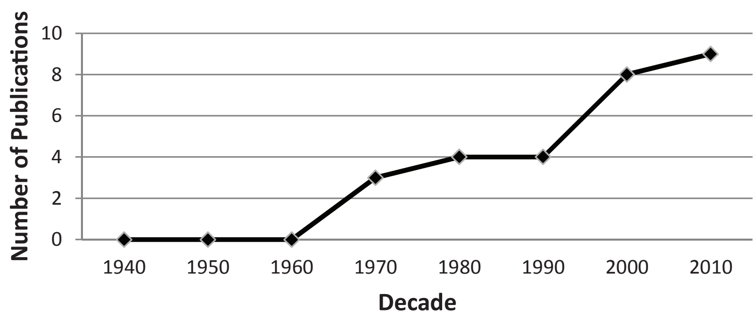

Figure 6.3: Annual GT publications, hydropower, $N = 9$.

to the capacity production constraint, assuming that oil or gas are available at a given level over time. The findings suggest that under different market structure and with the two game natures (Cournot and Stackelberg), each operator (hydraulic and thermal) may have relative advantage over the other. Similar work applying a Cournot–Nash model can be found in Villar and Rudnick [2003, 2004].

Fronza et al. [1977] analyze the optimal operation of the two-purpose water reservoir. Having two operators, each responsible for a certain purpose (e.g., irrigation and urban supply), and each with different and maybe opposed objective functions, suggests that a solution has to take into account the tradeoff between these two purposes. The authors demonstrate the application under both a non-cooperative solution where each purpose's operator maximizes its own objective, and a cooperative solution where the objective function is the sum of the benefits of the two operators. Under the non-cooperative scenario it is possible to find a solution such that the distribution of benefits is Nash-Equilibrium and Pareto-Optimal. Under the cooperative solution the joint benefits have to be distributed in one way or another, which is not addressed by the authors. The cooperative situation is shown to produce incremental benefits over the non-cooperative situation, suggesting preference for the cooperative situation.

The issue of reservoir operation under conflicting demands and under stochastic water supply is analyzed by Ganji et al. [2007].

A stochastic dynamic Nash game (PSDNG) model with perfect information about the stochastic nature of the water supply is developed and applied to the Zayandeh-Rud River basin in Iran. The results are compared with alternative reservoir operation models, i.e., Bayesian Stochastic Dynamic Programming (BSDP), Sequential Genetic Algorithm (SGA), and classical Dynamic Programming Regression (DPR). Results show that the proposed model has the ability to generate reservoir operating policies with regard to the operators' and the users' preferences.

An application of CGT to regulatory management of the electricity market is a unique contribution of Madani [2011]. The author demonstrates how CGT solutions can provide useful insights into how parties may use water and environmental resources and share any benefits of their cooperation. The work applies Nash and Nash–Harsanyi bargaining solutions to the Federal Energy Regulatory Commission (FERC) relicensing process in the US. The relicensing process allows owners of non-federal hydropower projects to negotiate their allowable operations with other interest groups (mainly environmental advocates). Linked games to expand the feasible solution range, and mitigate the 'strategic losses' are discussed and an FERC relicensing bargaining model is developed. The author extends the model to account for potential effects of climate change on the FERC relicensing process. One important finding is that the inclusion of climate change considerations, namely, increase in variability of water supply to the reservoirs, makes cooperation more attractive.

We conclude this section with the work by Gately [1974]. The focus of the work is regional cooperation in planning investment in electric power, with reference to the four states of the Southern Electricity Region of India (Andhra Pradesh, Kerala, Mysore, and Tamil Nadu). However, this work became known for its coined measure of stability of the cooperative arrangement — "Propensity to Disrupt" the grand coalition, which became a very popular index of stability for coalitional arrangements in various fields. The objective is to obtain a mutually acceptable basis for agreement, such that it is in each state's own interest to cooperate. The author estimates electricity production cost under various levels of cooperation in the four-state region, and engages the four states in various arrangements for sharing the joint costs, which may or may not be acceptable to the individual states. A player's propensity to disrupt is defined as the ratio between how much would the other players lose if that player refuses to cooperate, to how much that player would lose for refusing to cooperate. As was mentioned earlier, Straffin and Heaney [1981] modified the propensity to disrupt index to $N > 3$ players (in the case of Gately [1974] there are three states and the equations are specifically for three states). The modified propensity to disrupt a grand coalition by player j, SH_j, is:

$$\mathrm{SH}_j = \frac{\sum_{i \neq j} x_j - v(N-j)}{x_j - v(\{j\})} = \frac{V(N) - v(N-j)}{x_j} - 1, \quad j \in N$$

where x_j is the allocation to player j in the grand coalition. Negative values of SH_j reflect enthusiasm for the allocation x_j. Large and positive values of SH_j indicate that player j can threaten the members of the coalition, thus showing a high propensity to disrupt on player j's part.

6.4 Water pollution control

Water pollution is a transboundary phenomenon. Therefore, analytical frameworks applied to water pollution control can include international as well as domestic agents. Domestic and international water pollution control will be included in this section and not in the section on international water. While not necessarily related only to water, we would mention here the review by Finus [2003] that reviews the literature on forming coalitions in international environmental agreements, most of which deal with various types of pollution control.

Works in this category include interactions between the regulatory agency and the polluters that could be either individuals (irrigators, manufacturers) or cities, or even states or countries in cases of cross-border pollution. The works in this category have a strong component of external damages imposed by one or several polluters on the rest. In most works the objectives of the games are to find an optimal level of pollution or a scheme that achieves the socially-desirable level of

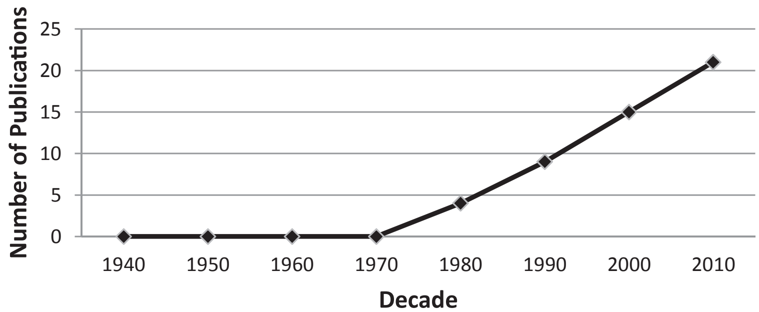

Figure 6.4: Annual GT publications, pollution, $N = 21$.

pollution, and the compensation to the victims. The annual number of published works in this category is presented in Figure 6.4.

We would start with the study by Kilgour et al. [1988], applying a CGT approach to control the load of chemical oxygen demand (COD) (as opposed to the conventional approach to regulate the concentration of the pollutant) is described and applied to a two-pollutant game. The work highlights the importance and difficulty to obtain fairness in the allocation of water pollution load control costs under certain closed water systems and the role of CGT in providing stable allocation solutions. One important observation from this work is that while all participants in the load control game benefit from cooperation, the most efficiently-abated player benefits the most and, in some cases, also un-proportionally. This is a major concern for instability in the cooperative game and needs to be addressed.

A couple of papers address the issue of agricultural pollution from pesticides and fertilizers. Alexander and Bhat [1998] develop a Stackelberg game-theoretic model of public policy formation with regulator and polluters that simultaneously determines endogenous price supports and pollutant quotas, as well as the optimal permissible water contamination. Their analysis distinguishes between the private and social opportunity costs of producing agricultural crops and using water as a repository for contaminants from agricultural sources. The contribution of this paper is in its ability to quantify the solution, including private and social benefits. Additionally, optimal production and pollution solutions will vary as the relative weights, which policy makers attach to different social constituents, change.

Another paper by Wetzstein and Centner [1992] addresses the issue of reducing the liability stringency level of chemical users in irrigated agriculture and replacing them with negligence standards. The work focuses on the allocation of the contamination costs and the protection level between agricultural producers and victims, using a dynamic game theoretic framework with moral hazards. Based on this analysis, a new institutional response is recommended to assign cost and protection levels.

An interesting application to pollution control when information about emissions and their impact is associated with uncertainty is presented in Abed-Elmdoust and Kerachian [2012]. The model addresses a situation known to be relevant in many countries, namely, lack of monitoring stations along the river. The river receives pollution loads from several dischargers and dischargers are penalized for any water quality violation as measured in the monitoring station. The suggested framework models the process of bargaining among load dischargers, subject to the assimilative capacity of a river (which is known). Signaling games can be utilized for modeling the bargaining among dischargers and developing Perfect Bayesian Equilibrium (PBE) strategies for pollution control. The authors develop an n-person iterated signaling game, which provides the stable PBE waste load allocation strategies among the polluters. The framework is applied to the Zarjub River in Iran, using seven pollution load dischargers.

An interesting application to a simplified case of the Aral Sea region is provided by Akhmedjonov and Suyundikov [2011] in the sense that it connects the allocation of the joint river basin water among upstream and downstream riparian areas to the salinity pollution (in the form of salt dust storms) in the region. While simplified to a two-country situation, still, the context of the model provides a clear application to the Aral Sea region. The paper examines if a partially cooperative water-allocation scheme, where a central authority chooses the two countries' respective abatement levels (of salt dust) after the countries individually choose per-unit taxes on water withdrawal, inducing the countries to withdraw water at the socially-efficient level. The authors find that the partial scheme managed by the central authority induces both countries to optimally choose to withdraw water at the socially-efficient level. While the relationship between water use and salinity pollution is much more complicated than the mechanism used in this paper, we still see in this paper a very unique application that should be further developed.

Fernandez [2002, 2009] develops differential games to examine wastewater pollution in basins (Rio Grande in the 2002 paper and Tijuana in the 2009 paper) along the Mexico–US border. The first paper [Fernandez, 2002] examines in a noncooperative and cooperative setting whether or not trade liberalization (affecting levels of industrial activities on the two sides of the border) affects emission levels. Using actual data, the analysis suggests that trade liberalization leads Mexico to reduce pollution in both cooperative and non-cooperative games. A more significant result is that, under cooperation and trade liberalization, emissions from both countries are reduced. The second paper (Fernandez, 2009) also develops a differential game that compares various incentives for wastewater pollution abatement control for the upstream and downstream countries under cooperation and noncooperation scenarios in the Tijuana Basin that is shared between Mexico and the US. Given the asymmetry between the two countries in terms of abatement costs, damages, and levels of emissions it is expected that different incentives will attract each of the countries. Game sharing rules with income transfer, such as the Shapley Value, Chander–Tulkens Rule, the Helsinki Rule [Salman, 2007], and the Egalitarian Rule are compared. In most cases of cooperation, there is a positive transfer of income from the victim (US) to the polluter (Mexico), mainly for reductions in flow and stock of pollution.

An interesting application of a cost-sharing problem of pollution control in the context of international water is presented in Wang and Ni [2007] and in an exact setting in Dong et al. [2012]. They refer to a river network in need of cleaning and the question of cost-sharing among the polluters. The contribution of this paper is in translating two international law rules, namely the Absolute Territorial Sovereignty and the Unlimited Territorial Integrity (UTI) into GT context. Three cost-sharing schemes are employed: (1) local responsibility sharing (LRS), (2) upstream equal sharing (UES), and (3) downstream equal sharing (DES). The DES is based on a new interpretation of the UTI. The authors show that the proposed three allocation schemes coincide with the Shapley Values allocation solution.

Another application of river pollution control in a context of international water is presented in Gengenbach et al. [2010]. The paper explores the role of voluntary agreements and the stability of coalitions when optimal treatment levels cannot be enforced by a central agency on all polluters. A transboundary pollution game with a unidirectional pollutant flow is modeled, where polluters are identical except for their location along the river. Partial coalitions are allowed. Findings suggest that the location of the coalition members does not affect the coalition stability, but it does affect overall basin welfare. The more upstream the members of the coalition are, the higher the overall welfare is because the positive externalities of cleaning accrue to a larger number of downstream water users (unintentional free riding).

In his work, Hurwicz [1998] addresses the design of mechanisms for solving pollution externalities as a game. While acknowledging the tragedy of the commons issues embedded in common pool resource games, Hurwicz points out that extending the game across space and time (super games, with infinite repetition of the Prisoners' Dilemma game) may lead to improved equilibrium compared with the tragedy of the common outcome.

A different approach to handle pollution control is suggested by Krawczak and Mizukami [1984] and Krawczak and Zioskowski [1985]. Assuming a non-cooperation arrangement in the region subject to pollution (a river in Krawczak and Mizukami [1984] and a lake in Krawczak and Zioskowski [1985]), the authors develop differential games where the polluters have to agree on the level of pollution in Nash and Stackelberg Structures in the 1984 paper and optimal treatment costs via the Nash Equilibrium in the 1985 paper.

Niksohan et al. [2009] develop and apply a cooperative trading discharge permit system that is equitable and efficient in the treatment costs for a set of polluters of a water body. The system consists of two main steps: (a) initial treatment cost allocation and (b) equitable treatment cost reallocation. A Pareto Front among objectives is developed in (a) with the objectives being the average treatment level of dischargers and a fuzzy risk of violating the water quality standards. The fuzzy risk is evaluated using the Monte Carlo analysis. The best non-dominated solution on the Pareto Front, which provides the initial cost allocation to dischargers, is selected using the Young Bargaining Theory [Young, 1993]. Then, in (b), several cooperative game theoretic approaches are utilized to investigate how the maximum saving cost of participating dischargers in a coalition can be fairly allocated to them. The final treatment cost allocation provides the optimal trading discharge permit policies. The approach is applied to the Zarjub River in the northern Iran.

Several works examine variations of games that aim at establishing markets for pollution permits. Poorsepahy-Samian et al. [2012] present a game for water and discharge permit allocation to agricultural zones in rivers that are shared by different agricultural polluters. The initial setting is a given (administrative) allocation of water rights and pollutant discharge permits. Then, trade in both water rights and pollution permits allows the forming of possible coalitions and optimal water and discharge permit reallocation among the coalition members to maximize coalitional characteristic function value. At that stage CGT solution concepts such as the Shapley Value and the Nucleolus are introduced to consider possible changes to the market-based allocations and increase the satisfaction of the individual polluters. The recommended water rights and pollution permits system is selected by minimizing the maximum regret in the system. The model was applied to the Karoon-Dez River system in Iran. Two new aspects have been introduced in this work: (1) a crop water production function accounts for water use and pollution emitted from the fields, and (2) the inclusion in the same model of both water rights and pollution permits.

Suzuki and Iwasa [2009] develop a model for integrated dynamics of human socio-economic choice and lake water pollution. Players can choose between a costly but cooperative option and a selfish option. Cooperation results in a reduced phosphorus discharge into a lake.

Each player's choice is affected by an economic cost and social pressure. Social pressure promotes cooperation. It is stronger when more players in the society are cooperative (conformist tendency) and when the problem at hand is a greater concern to society. The model allows for cooperation levels to differ between groups that have different social factors. Enhancement of the cross-group conformist tendency was found to be the most effective way to minimize differences in cooperation levels and to mitigate conflict between groups.

Tamura and Suzuki [1982] develop a simple CGT model with hierarchical structure of the polluters along a river. The model aims at regulating the basin-wide pollution discharge (calculated based on observed assimilative capacity of the water body) from all polluters. The CGT allocates the total allowed pollution among all polluters so that the social basin benefits will be maximized, and that each polluter in the set of cooperating polluters is satisfied.

And finally, Bhat et al. [1998] develop a Stackelberg [Von Stackelberg, 2011] Game between policy makers and agriculturalists that use chemicals in the production process to model public policy formation that simultaneously determines endogenous price supports and the nitrogen-use quota, as well as the optimal permissible water contamination in a water body. The authors are able to distinguish between private and social opportunity costs and are able to show that, with differences in the value of the private and social benefits attached to the pollutant, the weights assigned by the policy maker to social groups and situations will dictate the optimal production and pollution solutions.

6.5 Groundwater

Groundwater received the attention of GT modelers because of its common-pool resource nature and the congestion externality impacts among users. Works also address the possible conjunctive use of groundwater and surface water as well as the links between groundwater and ecosystems that depend on this source. In addition, several studies address the quantity as well as the quality of the available groundwater.

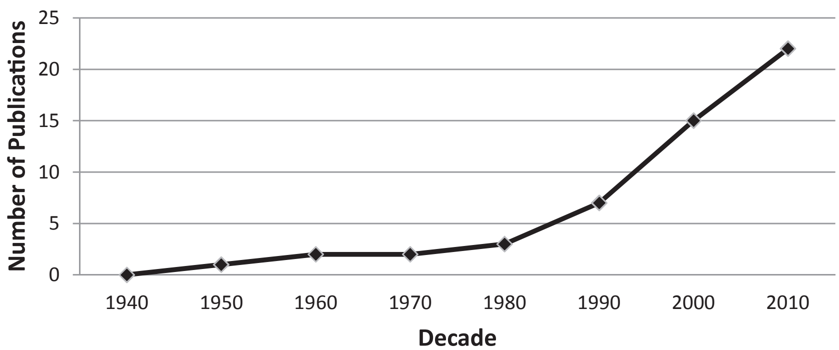

Figure 6.5: Annual GT publications, groundwater, $N = 22$.

Almost all works in this category address the externality nature of the public good nature of groundwater (congestion externality), and some address also the water quality externality associated with a public good management of groundwater aquifers. In most cases, the focus is on the individual users acting as strategic players and imposing negative externalities on all users. The annual number of published works in this category is presented in Figure 6.5.

Dinar [2001] develops a Nash Bargaining Model to an investment project in groundwater extraction, which determines both the optimal capacity of the well and the allocation of the costs and benefits among the cooperating users. Using two models that differ in their implementation complexity, the author shows that the models lead to the same result and thus open the gate for the use of the simpler model. The two procedures are illustrated for situations with and without side payments.

Dixon [1991] develops a GT model for an aquifer affected by lateral drainage externalities from a neighboring aquifer. This physical situation mimics the lateral drainage flows affecting regions in the west side of the San Joaquin Valley of California. The example uses an NCGT framework in which the author models behavior of irrigators that operate over two aquifers with unidirectional flow of saline drainage from one region to the other. Several behavioral patterns are modeled, including an open loop (with no interaction between decision makers) that leads to a Nash Equilibrium Prisoner Dilemma Solution; closed-loop (where agents take into account the decision of other agents); and collusive (cooperation) behavior that maximizes the two regions' total benefits and then splits the incremental benefits among the players evenly, using a Nash Bargaining Solution [Nash, 1953]. A dynamic model was applied to the Kern County region in California and the simulation was run for 60 years suggesting that collusion $\succ$ closed-loop $\succ$ open loop.

A similar approach was used by Negri [1989] who developed a common resource groundwater model to assess open-loop and feedback solutions in a dynamic GT setting. The author identified two types of inefficiencies in the management of the aquifer that were identified as the "dynamic externality": pumping cost externality and a strategic externality. The former one is the typical congestion externality that affects the pumping cost due to a lower water table; the latter one is the result of the competition among users to exploit the groundwater reserves. While the open-loop solution captures only the pumping cost externality, the feedback solution captures both externalities, and thus reflects the over exploitation of the common pool resource. As anticipated, the severity of the externality is higher as the number of users increases.

A similar idea is modeled in Provencher and Burt [1993]. They develop a common property groundwater dynamic game with feedback strategies by n players. One important finding in this work is the role of risk externality in addition to the stock externality and the pumping cost externality. Risk externality becomes an important factor that affects the efficiency of the groundwater extraction when the players are risk averse. The model is tested for deterministic and stochastic surface water supply to show the difference in the game solution under these two states of nature.

A model of group interaction and self-enforcement is presented in Georgakopoulos et al. [2006]. The authors refer to a situation that is common in many developing countries. Several water lords that own wells and have the capacity to pump water do provide water to other farmers for a fee. Well owners are rewarded for water sales. However, in some communities, water pumping is monitored by the well owners to prevent depletion and the subsequent increase in pumping costs to the owners. A fine is established and imposed on anyone pumping above the social pumping value that was established. A solution is achieved that reaches an equilibrium and prefers cooperation.

Levy et al. [1995] model the optimal strategy of a groundwater polluting agent facing regulations and possible levels of compliance that are associated with private and social costs. The model allows that regulatory agencies can carry out their mandate without incurring extra costs. The enforcement problem is modeled as a non-cooperative game. Several sub-game perfect Nash Equilibria are found for each level of compliance. One of these sub-game's perfect Nash Solution is the socially-preferred solution; the authors identify the conditions for its existence. The model is applied to the case of the pharmaceutical producer Ciba-Geigy's pollution of 126 groundwater wells in the Grand River watershed in Ontario, Canada.

Loaiciga [2004] compares cooperative and non-cooperative behaviors in aquifer management, using the quadratic programming model of aquifer water management. Using a stylized example, the author explains what cooperative aquifer management means and what the conditions are (mainly effective enforcement) for making it sustainable. Non-cooperative behavior is characterized by at least one user that does not internalize the pumping externalities on other users, violating water level constraints in a relatively short period of time, and leading to a collapse of the cooperative arrangement of the set of users. It is also shown that the total benefits from water use in non-cooperation are lower compared to the cooperative arrangement.

In a series of works, Madani and Dinar [2012a,b] demonstrated the performance of cooperative [2012a] and non-cooperative [2012b] institutions for sustainable groundwater common pool resource management. They introduce the concept of non-homogenous users. As is the situation in the real world, users of common pool resources may select available non-cooperative and regulatory exogenous institutions for managing the resource, as well as cooperative management institutions. All these institutions may increase long-term gains, prolong the life of the resource, and help to escape the tragedy of the commons trap. The 2012a paper formulates and applies several commonly-used cooperative game theoretic solution concepts, namely, the Core, Nash–Harsanyi, Shapley, and Nucleolus. Using a numerical example, the authors show how CPR (common pool resource) users can share the gains obtained from cooperation in a fair and efficient manner based on these cooperative solution concepts (management institutions). The 2012a paper discusses how different methods, such as application of the plurality rule and power index, stability index, and propensity to disrupt concepts, can help identify the most stable and likely solutions for enforcing cooperation among the CPR beneficiaries. In the 2012b paper the authors focus on non-cooperative management institutions that are associated with basic assumptions about the nature of behavior and decision making of the users in the short- and long run. Ignorant myopic management behavior is the worst type of management, which results in a rapid exhaustion of the resource and is the least profit to users, as suggested by "tragedy of the commons" literature. The most important conclusion from this work indicates that even within a non-cooperative framework, parties can obtain less tragic outcomes and improve their gains by acting smartly and considering the externalities; and by acting non-myopically and developing long-term exploitation plans.

A case study of groundwater management on the US–Mexico border with the players being the cities of El Paso and Ciudad Juarez is presented in Nakao et al. [2002]. The cities on the two sides of the border use the Hueco Bolson aquifer. Given their geographical and political positioning, there is no a-priori reason for cooperation, which leads to the Prisoner Dilemma solution. The authors develop a dynamic model of groundwater extraction and water table movement and compare four scenarios of cooperation and non-cooperation scenarios, including the non-cooperation status quo scenario, a Nash non-cooperative game scenario, a Nash cooperative bargaining scenario, and a social planner scenario that involves maximizing the sum of net benefits in both cities, that, in a second stage, has to be allocated among them. The difference between the status quo and the non-cooperative scenarios is that, in the status quo scenario, none of the players includes information about decisions by the other in its pumping strategy, while in the non-cooperative scenario such considerations are included. The results allow ranking of the scenarios with regards to the net present value of net benefits (over the 25 year horizon) such that social planner maximization $\succ$ Nash Bargaining $\succ$ Nash Non-Cooperative $\succ$ status quo, with Nash Bargaining Solution being very close to the social planner maximization. In addition, under the status quo the aquifer will be depleted after 18 years.

While most works reviewed in this monograph assume homogeneous conditions, Msangi [2004] develops a model for managing groundwater resources when there are asymmetries imposed by physical relationships in the hydrology or in the nature of the groundwater users themselves. With such characteristics of the users, the author derives the impact of the theoretical properties of non-cooperative and strategic groundwater pumping behavior in the presence of asymmetry and uses the insights from that model to address two specific empirical settings in Butte County in Northern California and in Hebei Province in Northern China. The model provides a better understanding of how asymmetric hydrological relationships could affect the performance of alternative policy instruments in the case of Butte County, and the effectiveness of alternative village-level institutions for managing groundwater and how they perform in the presence of transaction costs in the Hebei Province.

In Salazar et al. [2007] the economic benefit from use of groundwater for irrigation is the payoff of the farmers. The reduction of the potential environmental risk from agricultural pollution of the aquifer is the payoff of the community. The authors develop a regional model for the Alto Rio Lerma Irrigation District, located in the state of Guanajuato in Mexico and apply several solution concepts for a cooperative solution among these two players, including the Nash Bargaining Solution and the Kalai–Smorodinski Solution [Kalai and Smorodinsky, 1975] to suggest optimal and sustainable water and pollution loads to the aquifer.

Saak and Peterson [2007] develop a simple two-cell [similar to the setup in Dixon, 1991] and a two-period game to allow them to focus on the impact of incomplete information about aquifer transmissivity in shaping the common property equilibrium and its welfare distribution consequences. The Nash solution under incomplete information is compared to the socially efficient solution and to the Nash outcome under complete information. The interesting findings are that better information may either increase or decrease the equilibrium withdrawal rate, and also may either increase or decrease equilibrium welfare depending on a specific curvature property of users' net-benefit functions.

The work of Saak and Peterson [2007] is extended and generalized in Saleh et al. [2011]. They consider two groundwater management schemes — centralized and decentralized — with N users, in a dynamic game-theoretic structure. Several extensions make this work more relevant. First, including non-identical rather than identical users; second, they consider two different geometric configurations of the users overlying the aquifer — the strip and the ring configurations. The authors find different Nash equilibrium values, depending on the combination of the management schemes and the overlying configurations, which is very important for policy purposes.

Zadeh et al. [2009] apply a non-cooperative static and dynamic game model to a case where two municipalities and one agricultural operator pump groundwater. The model is applied under three scenarios: non-cooperative static, non-cooperative dynamic, and cooperative games. The results suggest that cooperation yields higher benefits compared with the non-cooperation scenarios, and that the dynamic game led to higher extraction compared to the results of the static game. These findings have important implications regarding the way we should model groundwater games.

Zagonari [2010] develops a model that evaluates economically, socially, environmentally, and institutionally sustainable groundwater management strategies that could cope with the impacts of climate change on aquifers in Brazil. Applying the Nash–Harsanyi Solution [Harsanyi, 1963] allows the author to evaluate negotiations regarding groundwater quantity and quality among the government, the economic sector and the social sector in Brazil. The author uses constant elasticity of substitution values to represent government preferences of assigning weights for various uses of water in Brazil by different sectors (economic and social), as they are reflected in the local legislation. Such an approach is very useful in deriving policy implications from various groundwater management arrangements in different watersheds in Brazil.

Recent works are concerned with the impact of groundwater level on adjacent and dependent ecosystems. Esteban and Dinar [2013] apply the concept of groundwater-dependent ecosystems in a cooperative game framework in the Eastern La Mancha aquifer in the Jucar Basin in Spain. The aquifer under consideration is divided into three sub-aquifers that are being overly exploited. Two types of externalities are modeled: (1) water extractions in each sub-aquifer impact water levels in neighboring sub-aquifers (extraction externality) and (2) the three sub-aquifers are also connected to an ecosystem and thus decisions in each sub-aquifer affect the health of the ecosystem (environmental externality). The model empirically shows how the uncontrolled extractions in each sub-aquifer affects neighboring groundwater users and also causes severe impacts to the linked ecosystem. The work estimates the value of cooperation and its stability with and without the environmental externality.

The reader is also referred to the work by Ostrom et al. [1994] for additional insights for this section. The authors include various common pool resources (fisheries, irrigation systems, forests, and groundwater basins) and do not necessarily focus on groundwater. Still, the use of both experimental and field data to test models of behavior in common-pool resource situations that are based on the theory of n-person, finitely-repeated games, is very useful for groundwater as well.

6.6 Allocations in water resources

The works that are reviewed in this section demonstrate the use of GT for allocation of joint costs and the resource itself among potential collaborators. Players in this group of works can be individual users, sectors, and states. Allocations are analyzed under both cooperative and non-cooperative settings. We review works that are based on game theory principles and on engineering principles. The annual number of published works in this category is presented in Figure 6.6.

We start with the works by Dufournaud and Harrington [1990, 1991]. The first work [Dufournaud and Harrington, 1990] develops a model of a joint water project in a river basin that involves three riparian areas and two time periods, using a linear programming framework

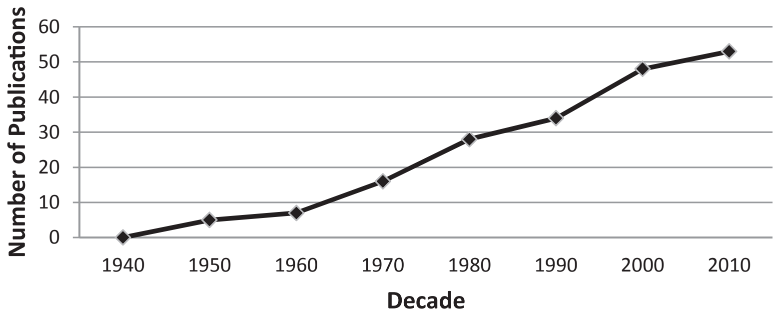

Figure 6.6: Annual GT publications, allocation, $N = 53$.

and a cooperative game concept. The costs and benefits of the joint water development project are evaluated for their relevance by using the propensity to disrupt concept [Gately, 1974]. In the second work, which applies a similar setting [Dufournaud and Harrington, 1991], the allocation of the joint costs and benefits is performed, using modifications to the model that satisfy the Shapley Value Allocation Scheme.[1]

An application of a simple Non-Cooperative GT model to assess the consequences of water market reforms and distribution of welfare among big farmers (corporations) and small farmers, resulting from implementation of water markets, is demonstrated by Galaz [2004]. The results provide interesting policy implications for countries that are in the process of modifying their water regimes. Policy makers should be aware that the institutional arrangements in the state affects the characteristics of the 'game', thus negatively affecting weak/small users, leading to their deprivation from access to water trade and even disruption ability.

An application of GT in the context of a water market is provided in Kong and Xu [2009]. The model follows a two-step dynamic game where the first step mimics the original allocation of the water rights by either a central agency or by a negotiation process among the players involved, and the second stage allows trade among the players to reach an efficient

[1] Additional reading on the Shapley Value, on the Core, and on Stable Sets can be found in Shapley [1953, 1967, 1971]; some of which is discussed in Section 4.2.

equilibrium. The first stage employs the Selten Equilibrium [Selten, 1975] and the second stage employs the Nash Bargaining Solution.

Krawczyk and Tidball [2006] present a method for the derivation of feedback Nash Equilibria in discrete-time finite-horizon non-stationary dynamic games. A particular motivation for such games stems from environmental economics, where problems of seasonal competition for water levels occur frequently among heterogeneous economic agents. These agents are coupled with a state variable, which is the water level. Actions are strategically chosen to maximize the agents' individual season-dependent utility functions. We observe that, although a Feedback Nash Equilibrium exists, it does not satisfy the (exogenous) environmental watchdog expectations. We devise an incentive scheme to help meet those expectations and calculate a feedback Nash Equilibrium for the new game that uses the scheme. This solution is more environmentally friendly than the previous one. The water allocation game solutions help us to draw some conclusions regarding the agents' behavior and also about the existence of Feedback Nash Equilibrium in dynamic games.

A method, the Generalized Allocation Scheme, for the allocation of joint costs among players who share the same service facility, is presented in Loehman and Whinston [1976]. This allocation scheme departs from the Shapley Value [Shapley, 1953] by considering that not all coalitional arrangements are possible. The Generalized Allocation method was already discussed in Section 3.3.

Okada et al. [1985] apply a hypergame (game with incomplete information) framework to the Lake Biwa conflict in Japan. This dispute constitutes a typical example of a water allocation conflict where downstream users would like more water from the upstream who control the major source of the water. The incomplete information is modeled by having each player with misperceptions about the other players' preferences. The game is conducted in two stages. First, a set of allocations reflecting the preferences of the players is provided, with some a-priori ranking of the various outcomes. Then, in the second stage, the stability of the proposed allocations is evaluated based on Fraser and Hipel [1979, 1984].

In a somewhat similar line of work, Pande and McKee [2007] assess how uncertainty in a policy variable affects the "allocation solution" in consensus-based decision-making processes. In consensus-based bargaining games a player in his turn makes a proposal that yields payoffs to all participants that are no less than the expected payoffs that each can obtain from the previous proposal. If this condition will not be fulfilled some of the non-proposing players will object the proposal and the negotiations will collapse. Using the Rausser–Simon Bargaining Model [Rausser and Simon, 1991, Carraro et al., 2005, 2007] the authors model two relevant consensus-based negotiation processes, one of which is the California negotiation regarding the transferability of water rights for environmental protection and the degree of supporting infrastructure. The most important finding is that, in both case studies, the bargaining solution under uncertainty deviates from the solution under certainty and the level of deviation increases as uncertainty increases.

Otten [1993] revisits the alternate cost avoided (ACA) method used in the Tennessee Valley Authority studies and provides an axiomatic characterization of the ACA-method on a certain class of cost games with a fixed player set, as well as on a class of cost games with a variable player set, using a reduced game property. The equation used for the ACA is:

$$\mathrm{ACA}_i(c) = \mathrm{SC}_i(c) + \frac{c(\{i\}) - \mathrm{SC}_i(c)}{\sum_{j \in N}(c(\{j\}) - \mathrm{SC}_j(c))}\mathrm{NSC}(c), \quad \forall\, i \in N$$

where $c(\{i\}) - \mathrm{SC}_i(c)$ represents the alternate cost avoided by including player i in the joint project, $c(\{i\})$ is cost to player i, SC are separable costs, NSC are non-separable costs. The author shows that under certain conditions the ACA method coincides with game theoretical methods such as Shapley.

Analysis of various Non-Zero-Sum-Games to social dilemmas, including bargaining over water allocation, is presented in Rabow [1988], where a general strategy of Cooperation with Minimum Sanctions (CMS) is developed and applied to Prisoner's Dilemma (PD) situations. The author shows that in many cases of a one-shot game the Prisoner's Dilemma is the only outcome. The most important finding is that a generalized cooperative PD strategy Tit-for-Extended Tat is developed, which, for the special case of iterated PD, reduces to the Tit-for-Tat strategy (Developed by Anatol Rapoport: explained in Davis, 1983) that has been found to be so effective for that case. The mechanism that makes such a strategy effective in the real world is a reputation for cooperation, which a player can establish through a record of cooperation. The result, that cooperation is much more rational than previously believed, might encourage cooperation in the real world. An example of allocation of a fixed source of water between high value recreation and low value (but essential) irrigation suggests that an interpersonal utility comparison is necessary, which eliminates the Nash Bargaining Solution from being considered.

An analysis of possible cooperation among individual farms in a water district that faces the possibility of water transfer to an urban water district is analyzed in Rosen and Sexton [1993]. The model is applied to a water trade project between the Imperial Irrigation District and the Metropolitan Water District of Southern California. The results suggest that substantial intra-organizational conflict (among the farms) can emerge in response to certain transfer proposals, and this conflict may derail the transfers, even if the overall payoff to all parties is non-negligible.

An application of several modifications of CGT solution concepts to the allocation of water resources in a river basin is presented in Sadegh et al. [2010], and applied to the Karoon River Basin in Iran. The authors develop a new methodology based on crisp and fuzzy Shapley games for optimal allocation of inter-basin water resources. (In a crisp game the agents are either fully involved or not involved at all in cooperation with some other agents, while in a fuzzy game players are allowed to cooperate with infinitely different participation levels, varying from non-cooperation to full cooperation.) In the proposed methodology, initial water allocations are obtained using an optimization model considering an equity criterion. In the second step, the stakeholders form crisp coalitions to increase the total net benefit of the system as well as their own benefits. A crisp Shapley Value game is used to reallocate the benefits produced in the crisp coalitions. Lastly, to provide maximum total net benefit, fuzzy coalitions are constituted and the participation rates of water users to fuzzy coalitions are optimized. Then, the total net benefit is reallocated to water users in a rational and equitable way using the Fuzzy Shapley Value game. Given fuzzy game ν and fuzzy coalition s, the fuzzy Shapley Value of player i with participation rate s_i is presented as:

$$\varphi_i(v) = \sum_{i \in T \subseteq N} \frac{(N - |s|)!(|s| - 1)!}{N!} \left[v\left(s \sum_{j \in T} S_j e^j \right) - v\left(\sum_{j \in T \setminus i} s_j e^j \right) \right]$$

In a similar study, Sadegh and Kerachian [2011] add two new solution concepts for fuzzy cooperative games, the Fuzzy Least Core and Fuzzy Weak Least Core, apply them to the same site, and compare the results to those of some traditional fuzzy and crisp games in Sadegh et al. [2010]. They show that the proposed fuzzy solution concepts are more efficient than the crisp solutions.

An application of the Nash Bargaining Solution to a real water allocation problem in the Mexican Valley in Mexico, one of the most critically water-scarce regions in the state, is presented in Salazar et al. [2010]. The author develops a three-player Non-Symmetric Nash Bargaining model, which solves an optimization problem with nonlinear objective function and linear constraints. It was found that for all water availability scenarios there is no water distribution strategy that satisfies the domestic demand. This calls for investment in additional system upgrades along with improved efficient uses.

Sechi et al. [2013] criticizes the existing cost recovery system of water projects in Europe, and especially cost recovery of complex systems that face multipurpose demands. This work presents a methodology to allocate water service costs in a water resource system among different users that attempts to fulfill the requirements of the Water Framework Directive (WFD) of the EU. Using a CGT framework with a mathematical optimization model, the water system cost allocation is valued as a game in which it is necessary to determine the appropriate payoff for each player (user). As in previous works, the characteristic function of the various coalitions is evaluated using an optimization model that yields the core of a cooperative game. The methodology was applied to a multi-reservoir and multi-demand water system in Sardinia, Italy.

Applications that deal with acute allocation issues can be found in several works: Serghini [2002], who addresses the fairness issues in multipurpose projects in Morocco by comparing 10 allocation methods used, and concluding that the CGT ones are the most credible; and Souza Filho et al. [2008] addresses the very acute problem of water allocation along a water course and non-availability of water to tail-users on an irrigation system in developing countries, due to unregulated upstream diversions. This suggests a game to take into account the free riding of certain users taking advantage of the ability of the regulatory agency. Suzuki and Nakayama [1976] also refer to the fairness in allocation of costs and benefits of water projects aimed at building a dam to provide water to irrigation and to several urban centers from two rivers, using the Nucleolus Scheme. Tijs and Driessen [1986] review various cost allocation methods that are based on the Nucleolus and the Shapley Value, and introduce the Cost Gap Allocation method, which is based on the τ-value. They show, using the TVA case, that the CGA coincides with the SCRB method and with several of the proposed methods used by the TVA in the 1940s. More examples can be found in Tisdell and Harrison [1992], Wang et al. [2003, 2008], Wang [2011] and Young et al. [1980, 1982].

6.7 International/transboundary water

International water is among the fields to which game theory was applied the most during the past 25 years. Most applications dealt with the cooperative nature of sharing water and how cooperation is likely to provide stability to the basins under conflict. Some works apply Non-Cooperative Game Theory frameworks and demonstrate how under such behavior solutions are possible for water conflicts. Players in the works reviewed in this category include states and the games that may introduce externalities, depending on the geography of the shared rivers. Some of the works, especially in recent years, introduce issues related to climate change such as the stochastic supply of water

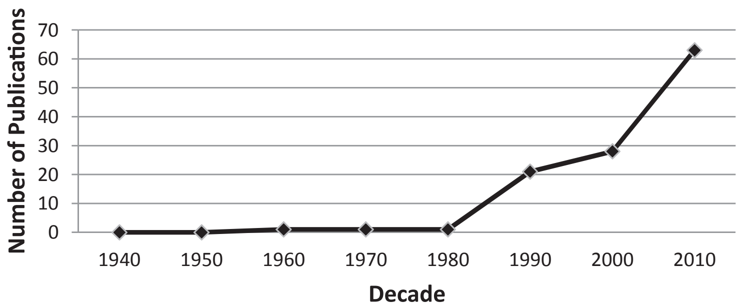

Figure 6.7: Annual GT publications, international, $N = 63$.

in the river. The annual number of published works in this category is presented in Figure 6.7.

We will start with the earliest application known to us. Rogers [1969] develops a CGT framework and applies it to the conflict in the Ganges River Basin at that time. This is the first known work to us of application of GT to international water. The author identifies issues which are of mutual interest to India and Bangladesh, such as navigation, flood control, and irrigation, and builds an optimization mathematical programming model linked with CGT solution concepts that allow us to realize the cooperation potential between the two riparian nations. This will result in significant benefits to each. The author is not dealing with the allocation of the cooperation gains in this work. The model in Rogers [1969] was refined and expanded in Rogers [1993] and Rogers [1994] to include both unidirectional externalities (mainly floods and pollution originating in India and affecting Bangladesh) and allocation schemes such as the Nucleolus and the Shapley Value.

Following on the Ganges conflict, Anandalingam and Apprey [1991] develop a Non-Cooperative framework to address the conflict resolution options in an international river basin. They use a Stackelberg Game Structure with an external arbitrator that initiates the moves in the negotiation.

In a series of works, Becker and Easter [1991, 1995, 1997, 1999] model Great Lakes Basin management issues among Canada and various states in the US. In their 1991 work they consider alternative diversion restrictions and their impact on the basin and players' (states in the US and provinces in Canada) benefits. In the 1995 work they compare the results of two game structures: 2 players (US and Canada) and 8 players (6 US states and 2 Canada provinces) to the Social Planner Solution. The results suggest that states do not divert water necessarily because they stand to gain but because they may lose more if they do not. The 1997 work considers the economically desirable diversions and how the gains from such diversions should be distributed among the players. The work shows that in most cases, new institutional arrangements will be needed before agreements can be reached. A similar approach is used in the 1999 work, but here the approach addresses different configurations of the lakes that are being regulated (starting from one lake and ending up with all lakes.)

A series of works develop and apply the concept of interlinked games to international water. This concept is very useful in the case that deals with conflicting issues that lead to gridlock. The existence of issues that have asymmetric interest on the part of the parties involved may lead to an acceptable set of solutions.

Folmer et al. [1993] introduce the concept of interconnected games and show its relevance for addressing international environmental problems, especially in replacing the need for side payments to maintain cooperation. They introduce two types of interconnected games: Direct Sum Games and Tensor Games. In the former, all the constituting isolated games are games in strategic form and in the latter they are repeated games. In both cases the interconnected game can be interpreted as a multiple objective game, but only in the setting where a trade-off is made for the vector-payoffs. Using a simple example of international water pollution they demonstrate the potential advantages of allowing countries to 'trade' concessions across issues (e.g., pollution certificates and trade of goods) under negotiation and describe what circumstances best lend themselves to such a trade. The advantage of the interconnected game framework is that countries can now condition their choice of actions in the environmental area to outcomes previously observed in the trade arena, and vice versa. This capability enriches the set of Nash Equilibria and maximizes the sum across countries of the obtainable payoff values.

Bennett et al. [1997, 1998] apply the idea of interconnected/linked games to the problem of international water quantity and quality externalities. The authors argue that in the presence of unidirectional externalities the traditional game theory approach produces unsatisfactory solutions leaving the victim to pay and unable to transfer payments to incentivize the upstream country to change its practices. Instead, the authors suggest that nations in weak negotiating positions try to improve their leverage by linking issues. If the linked issues are selected carefully, it can generate outcomes that cannot be obtained when games over issues are modeled separately. The authors recommend using the Interconnected Game Modeling approach for international rivers. They demonstrate the Interlinked Game Model for the case of the Aral Sea in Central Asia and in the cases of the Euphrates and Orontes River Basins in the Middle East.

A similar approach has been implemented by Pham Do et al. [2012] to the case of the Mekong River Basin. They analyze whether issue linkages can be used as a form of negotiation on sharing benefits and mitigating conflicts in the presence of unidirectional externalities, such as in the case of the Mekong. In particular, if the linked games are convex, the grand coalition is the only optimal level of social welfare. An extension of their work to include multi-level linked issues is provided in Pham Do et al. [2014].

The last work we include under interlinked games is the one by Just and Netanyahu [2000] where they demonstrate that achieving strict dominance of the linked game is not trivial and that results and implications depend on the structures of the isolated games. Another application of the interconnected game concept can be found in Just and Netanyahu [2004] where they consider modeling bilateral agreements for sharing common pool resources under conditions of unequal access. Their work shows how game structure and benefits suggested by interconnected games are modified when the victim pays strategies are removed from the feasibility set.

The peace agreement between Jordan and Israel, and Egypt and Israel, and the establishment of the Palestinian Authority led to several attempts at addressing the water conflict between Israel and its Arab neighbors, which at that time were very promising. Several works use the relative advantage of the players in a game of water creation and/or exchange.

Dinar and Wolf [1994a,b, 1997] develop the concept of water for technology in the lower Nile Basin. They demonstrate the economic rationale for exchange of technology and knowhow for the water saved by using that technology. If allocations (water or income) are assumed among countries with some level of hostility, political considerations which are usually not incorporated in economic analysis can hinder or even block the most efficient arrangement. Dinar and Wolf [1994a,b, 1997] demonstrate, using several CGT concepts that are amended by political models (PRINCE Political Accounting System; and the Generalized Shapley Value with political probabilities), how incorporating political considerations in the analysis may provide a more acceptable regional solution compared to the economic-related allocations.

A different focus on possible cooperation via exchange is discussed in Brill et al. [1999]. The authors depart from the situation of water scarcity in the Gaza Strip and technological capacity for wastewater treatment in Israel. They suggest the following scheme that does make a lot of economic sense: wastewater from Gaza will be sent to Israel for treatment and fresh water (either treated or desalinated), in exchange, will be sent from Israel to Gaza. The cooperative Nash Bargaining Solution and the non-cooperative Nash–Cournot solution [Tirole, 1988] are compared. The results suggest that as scarcity level increases, the gap between cooperative and non-cooperative solutions increases. More examples on the application of GT to water conflicts in this part of the world can be found in Becker et al. [2001]. An example of application of game theory to the sharing of the Mountain Aquifer between Israel and the Palestinian Authority is analyzed in Netanyahu et al. [1998], using both cooperative and non-cooperative bargaining GT and other solutions and suggesting that GT approaches are robust with regards to demand elasticity, user costs and pumping costs.

Additional work was done on the potential for regional cooperation in water allocation and use between Israel and the Palestinians in light of increasing regional scarcity. Yaron [2002] suggests several solutions to be considered using the entire arsenal of water resources in each entity showing relative advantages in its production and use.

Interest has grown in the first part of the 21st century as more work was published on aspects related to international water treaties — treaties on management of joint international waterways. This line of work addresses the so-called: 'self-enforced agreements', 'stability of coalitions', and 'mechanism design' of treaties in light of climate change. Review of the literature in this field can be found in two PhD dissertations published recently [Ansink, 2009, Moes, 2013].

Kilgour and Dinar [2001] address variation in water supply and its impact on the stability of international agreement. They claim that most water allocation agreements refer to the long-term mean flow and as such treaties are unable to accommodate variations in conditions. They develop a flexible mechanism that produces a Pareto-efficient Allocation for every possible flow volume in a river, which can also be extended to accommodate other kinds of variation, such as changes in water demand. They apply the mechanism to historical water flow data for the Ganges, using stylized water demand relationships for India and Bangladesh. They derive equilibrium negotiation solutions and conclude that variable allocation substantially outperforms fixed allocation, improving regional welfare by at least 10%.

Several works focused on issues related to specific basins around the world. Frisvold and Caswell [2000] analyze common water sources and pollution problems on the US–Mexico border. Using game theory, the work draws policy lessons for institutions funding border water projects. The diversity and geographic dispersion of water conflicts suggests potential for applying the Interconnected Game Approach to US–Mexico water negotiations. Guner [2008] applies Evolutionary Game Theory to explain how issues of water and territory dominate relations between Turkey and Syria, upstream and downstream riparians in the Euphrates and Tigris Basin. The analysis suggests that stability in the basin relations does not depend upon the values territory and water represent for the fitness of Syrian and Turkish foreign policies. No evolutionary stability is possible unless doves are cooperative toward hawks. If doves are cooperative toward hawks, the unique evolutionarily stable outcome implies their extinction. Riparian relations will ultimately evolve into mutual intransigence, hence leading to disagreement on any cooperative solution. Teasley and McKinney [2011] model water and energy resources of the Syr Darya Basin, considering transboundary cooperation and benefits sharing. The authors use a river basin model and different methods for allocating the benefits of cooperation such as the Shapely Value, Proportional Shares, Equal Shares, the Nucleolus, and Nash–Harsayni. All but the Shapley Value result in allocations that are more likely to be violated and are less stable. Eleftheriadou and Mylopoulos [2008] implement game theoretical concepts in the case study of Greek–Bulgarian negotiations on the Nestos/Mesta transboundary river. They show that implementing interconnected games widens the countries' available options and contributes to the avoidance of unreasonable outcomes while balancing uneven "power" potentials. Hamandawana et al. [2007] analyze, using a Game Theory framework, the interstate conflict between Angola, Botswana, and Namibia over the Okavango River's shared water. Houba et al. [2013] model the welfare effects in the year from strengthening the Mekong River Commission's (MRC) governance versus joint management of the entire Mekong River Basin (MRB). Their analysis shows that the Lower Mekong Basin (LMB) has no incentive to negotiate with China and is better off strengthening the MRC's governance instead.

Additional works that we should mention include Beard and McDonald [2007] who applied the concept of Time Consistent Cooperative Dynamic Games [Filar and Petrosjan, 2000] to an international basin with water-right trading. Beard [2011] reviews the literature on the river-water sharing problem and discusses that literature with respect to the connection to the bankruptcy literature, and models of directional flow, which are detailed below. Thiel [2004] criticizes the use of the Basin-Wide Welfare Maximization model as a basis for treaties in EU international rivers. Using GT concepts applied to the case of the five Portugal–Spain shared basins (Luso-Spanish Convention), the analysis rejects a basin-wide welfare economic evaluation of the negotiations on transnational agreements. Instead, it suggests that mutual payments as described here might only be applied in the long term and only to specific transboundary spillover welfare issues.

A series of studies focused on achieving stable agreements in stylized river-basin structures followed the seminal work by Ambec and Sprumont [2002]. These authors refer to a group of agents arranged sequentially along a river, and are characterized by a given set of preferences for water and money. The aim is to find an allocation that will be efficient, stable (in the sense of the core), and fair. They show that a cooperative game of this problem is convex, thus implying a large core that would guarantee the three requirements: efficiency, stability and fairness. They prove that only one welfare vector in the core can satisfy the three requirements — the allocation based on the marginal contribution vector that corresponds to the order of the agents along the river.

The work by Ambec and Sprumont [2002] was extended by Ambec and Ehlers [2008] to include two extensions — a satiation point in the benefit function of the players along the river, and unidirectional externalities. The authors observe that the cooperative core might be empty; instead, they suggest a unique allocation of the water — the downstream incremental distribution — is the unique distribution which is both fair–according to the "aspiration welfare" principle — and satisfies the Non-Cooperative Core lower bounds. In addition, it satisfies all core lower bounds for all connected coalitions if and only if each agent's individual rationality constraint is independent of the behavior of the other agents.

The ideas in Ambec and Ehlers were further extended in Ambec et al. [2013] to include fluctuations in the water flow of the river due to droughts. Their river geography is again a sequential river where the players along the river agree (or not) to release an amount of river water in exchange for a negotiated compensation. The work addresses the vulnerability of such agreements to reduced water flows. Among all types of agreements, they find one, which is self-enforced under the most severe drought scenarios, the upstream incremental allocation, that assigns to each country its marginal contribution to its followers in the river. Its mirror image, the downstream incremental allocation, that featured in previous works, is not sustainable to reduced flow at the source. They demonstrate the usefulness of the model in the case of the Aral Sea Basin.

Ansink and Ruijs [2008] address the sharing problem by assessing the effect of climate change and the choice of a sharing rule on stability of the agreement using a game theoretic model. The results of their work suggest that a decrease in mean river flow decreases the stability of an agreement, while an increased variance can have a positive or a negative effect on stability, depending on the institutions in place. An agreement where the downstream country is allocated a fixed amount of water has the lowest stability compared to other sharing rules.

Another work that addresses the impact on stochastic river flow in the stability of treaties is Ansink [2009]. The author tries to find water allocation agreements that can be self-enforcing under stochastic situations. An agreement is an outcome of a bargaining game which is the result of a repeated extensive-form game in which countries decide whether or not to comply with the agreement. The work suggests that, for sufficiently low discounting rates, every efficient agreement can be sustained in subgame perfect equilibrium. The solution induced by this particular agreement implements the downstream incremental allocation [see also Ambec et al., 2013], an axiomatic solution to water allocation that assigns all gains from cooperation to downstream countries.

A work that responds to points raised in Dinar et al. [1992] and Ambec and Sprumont [2002] is Houba [2008]. This contribution addresses the fundamental critique in Dinar et al. [1992] on the use of GT in river basin management: People are reluctant to do monetary transfers unrelated to water prices, and game theoretic solutions impose a computational burden. The authors develop a single optimization program that significantly reduces the computational burden, where water prices and property rights result from exploiting the Second Welfare Theorem. An application to a bilateral version of the Theoretical River Basin Model in Ambec and Sprumont [2002] is provided.

Van den Brink et al. [2010] expands the results of downstream incremental allocation in Ambec and Sprumont [2002] by adding a class of weighted hierarchical solutions [Kononenko, 1974] that satisfy the 'Territorial Integration of all Basin States' principle for sharing water of international rivers (in the international water law). They find that when all players have increasing benefit functions, every weighted hierarchical solution is core-stable. In case of satiation points, every weighted hierarchical solution is independent of the externalities.

Other works worth mentioning include: Choi and Lee [2008] who address a transboundary river between South and North Korea in the Bukhan River, showing cooperation is the best option for South and North Korea. Colat-Parros [1999] shows that cooperative sharing of international waters results in minimal water-resource depletion compared to uncooperative sharing. Dinar et al. [2007, 2013] demonstrate the use of Cooperative Game Theory concepts in international river basin allocation conflicts, and uses, as an example, the Syr Darya. Kindle [2009] views the Canada–US bulk water export issue as a conflict, and proposes strategies (using Game Theory and legal approaches) that Canada could take to protect its freshwater. Kolodziej et al. [2006] define an allocation of joint water sources with external disagreement of interests as an n-person Non-Cooperative Game, and solve this disagreement, using the Parallel Evolutionary Strategy HGS Nash.

Guldmann and Kucukmehmetoglu [2002], Kucukmehmetoglu and Guldmann [2004], Kucukmehmetoglu [2009], Kucukmehmetoglu et al. [2010], and Kucukmehmetoglu [2012] develop mathematical programming models that allocate the waters of the Euphrates and Tigris Rivers to agricultural and urban uses in Turkey, Syria, and Iraq, while accounting for water conveyance costs. CGT concepts (Core, Shapley Value) are used to identify stable water allocations, under which all three countries find it beneficial to cooperate. Lee et al. [2011] modeled multi-purpose dams and allocation of the benefits and costs associated with them between North Korea and China, using a cooperative two-person Non-zero-sum Game. Mahjouri and Ardestani [2010] apply game theory concepts to interbasin water transfers in Iran. Missfeldt [1999] compares various game theory approaches to the handling of transboundary water pollution. Wang et al. [2013] apply a relative utility function combined with the asymmetric Nash Bargaining Method to analyze the trans-jurisdictional conflict between water quantity and water quality in the Zhangweinan Canal Basin in China. Wu and Whittington [2006] apply CGT concepts such as Core, Nucleolus, and Shapley Value to Nile water conflicts. Yang et al. [2008] model the water conflicts between Beijing and Hebei province, which are in the upstream and downstream of the Guanting Reservoir Basin (GRB), using Non-Cooperative and Cooperative scenarios; and van der Laan and Moes [2012] model international river pollution problems. The unique feature of the model is that each player along the river benefits from activities that cause pollution downstream, and, at the same time, players (except the first one) are also harmed by pollution that originates upstream. Using principles from international water law the authors determine that cooperation is the best strategy and suggest ‘fair’ ways of solving the pollution problem, based on property rights’ doctrines from international law, such as Absolute Territorial Sovereignty, Unlimited Territorial Integrity, and Territorial Integration of all Basin States.

6.8 Water conflict and negotiation

Application of GT to the field of water conflict and negotiation has also increased over time, especially with the application of NCGT approaches. Works in this category include all types and levels of players that have been mentioned in the previous categories. The annual number of published works in this category is presented in Figure 6.8.

A series of papers by Carraro et al. focuses on various angles of conflict and negotiations in water resources. Carraro et al. [2005] review the applications of Non-Cooperative Bargaining Theory to water-related issues, which fall under the category of formal models of negotiation. This group of models identifies the conditions under which agreements are likely to emerge, and specify their characteristics. Once these are identified and specified, models can help policy makers in devising the “rules of the negotiation game” that could help obtain a desired result.

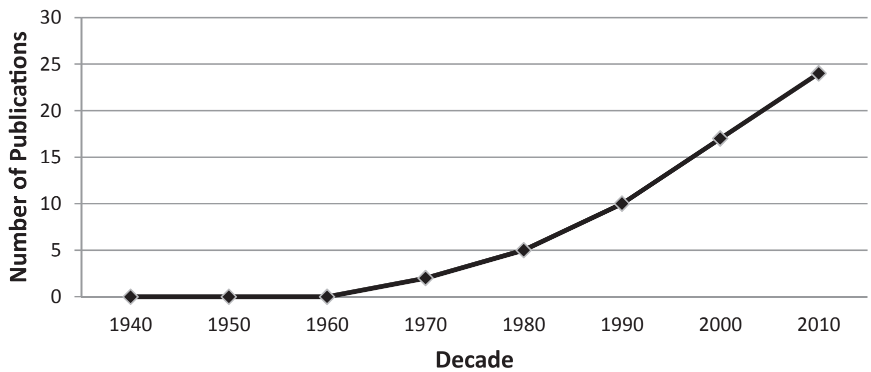

Figure 6.8: Annual GT publications, negotiation, $N = 24$.

The paper discusses the Non-Cooperative Bargaining Models applied to water allocation problems in the literature, with particular attention placed on those directly modeling the process of negotiation. In addition, they review Negotiation Support Systems (NSS) developed to support the process of negotiation. NSS have not yet been applied in real-life negotiation.

Carraro et al. [2007] review and demonstrate the applications of Non-Cooperative Bargaining Theory to water management problems. They demonstrate the usefulness of the bargaining approach for groundwater allocation, surface water allocation, water quality regulation and allocation of international water among riparian countries. They demonstrate the use of concepts such as auction games and issue linkage. They suggest that assessment of game theoretic models in analyzing past behavior, or in predicting future agreements, "will not be complete as long as utility functions and constraints are assumed by researchers, rather than derived from actual behavior" (p. 346).

Carraro and Sgobbi [2008] provide insights into asymmetries and uncertainties of the negotiation process by using a NCGT approach, applied to natural resources such as water. The results suggest that uncertainty affects players' behavior and modifies the likelihood of a self-enforcing agreement to emerge.

Additional works that are relevant to this group include Marchiori et al. [2012a,b], Marchiori [2010], Stratton et al. [2008], Sgobbi and Carraro [2011], and Rausser et al. [2011].

Another group of works uses the graph model approach. Kilgour et al. [1987] apply a graph model to address conflict and understand the moves in the case of a multiplayer conflict. The graph model is different than other approaches in that it takes outcomes, rather than individual decisions, as the basic units for describing a conflict. The model is applied to the case of a conflict over North Dakota's diversion off the Missouri River for irrigation that is then creating pollution in the Red and Souris Rivers that flow into Canada. Additional applications of the graph model can be found in Hipel and Ben-Haim [1999], Hipel et al. [1994], Hipel et al. [1974, 1976], and Hipel and Walker [2011].

Adams et al. [1996] apply the Rausser Simon Framework for non-cooperative, multilateral bargaining that can be used to conceptualize negotiation processes, where the outcome of the negotiation process depends crucially on the "constitutional" structure of the game: the input each group has in the decision-making process, the coalitions of groups that can implement proposals, the scope of the negotiations, and the outcome if the parties fail to reach agreement. The model is used to analyze water policy negotiations in California.

Thoyer et al. [2001] applies also the Rausser and Simon Model [Adams et al., 1996] to assess directions of reforms in the Adour Basin in the southwestern France. Negotiations over decentralization such as water rights handling, taxes, investment, etc., are modeled in a negotiation game between farmers, basin authority, central government, and environmental groups.

Other relevant works include Hermans [2003] who applies two methods for conflict exploration, (1) analysis of options and (2) argumentative analysis, to water resources management in the Philippines; Lussier et al. [1989] who applied GT-based techniques of conflict analysis to the Shoal Lake water supply conflict in southeastern Manitoba, Canada and Sakakibara et al. [2002], who apply a graph model to conflict resolution for cases with incomplete information.

Another line of work applies the Nash Bargaining Theory in a two-level negotiation for water allocation. Richards and Singh [1997] demonstrate the interaction between international and domestic levels of negotiation over an international river basin. This kind of two-level negotiation is especially important when local interests for water may conflict with national interests.

Saleth et al. [1991] applies several bilateral and multilateral bargaining approaches, including Nash Bargaining Theory, and the Harsanyi Approach [Harsanyi, 1986] to a thin-water market in a watershed in Illinois. Important findings are that the institutional features in the region, such as the size of the market, the size of the farms, and the information structure affect the outcome of the negotiation process.

Soubeyran and Tomini [2012] assess the risk of a conflict between riparians sharing international water. Using a Nash Bargaining Framework they show that the risk for conflict increases as level of scarcity increases and as asymmetry in water productivity is higher.

6.9 Water and the environment

We distinguish this section from Section 6.4 (Water Pollution Control) in that the models that are included in this section capture the economic value of the environment rather than regulating its pollution. A group of works applies GT models to issues related to changes in water projects' impacts on the environment and the environmental flow needs. Some of the reviewed works introduce the environment as a passive player that is protected by a priori regulation by the government. Another group of works has the environment as a player with objectives and strategic behavior. The annual number of published works in this category is presented in Figure 6.9.

Hanemann and Dyckman [2009] document how the State of California has failed to organize itself effectively to resolve the conflict about whether and how to transfer water from the Bay-Delta to users elsewhere in the state, and make a decision on how to manage the Delta of the San-Joaquin and Sacramento Rivers. The strategy consistently adopted by the State was to encourage the main parties — agricultural and urban water diverters, and fisheries and other instream-protection interests — to work out a solution among themselves, rather than

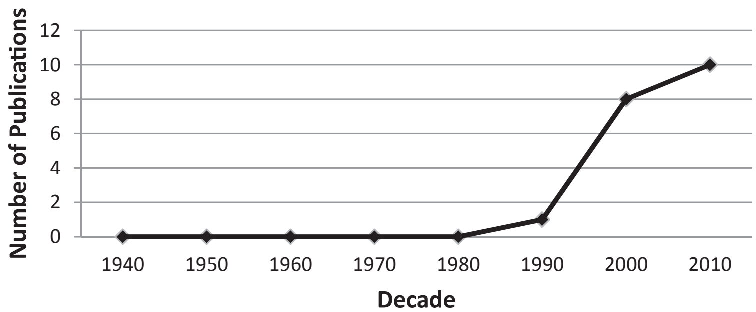

Figure 6.9: Annual GT publications, environment, $N = 10$.

imposing one externally. The authors show that a bargaining solution is unlikely to exist because of the extreme opposition of interest among the parties.

Using the same environmental conflict, Madani and Lund [2012] argue that the Delta problem is of a Prisoner's Dilemma nature, in which stakeholder self-interest makes cooperation unlikely within a reasonable time frame. However, because the core of the Delta conflict changes as the unsustainable future becomes more widely understood, the problem has characteristics of a Chicken Game, where cooperation is in everyone's interest, but it is unlikely because parties deviating from the status quo are likely to bear more of the costs of a long-term solution.

A third strand of work refers to the integrated ecosystem services and the minimum flow that is needed in order to secure such set of services. Buckley and Haddad [2006] address the problem of ecological restoration within a mosaic landscape in which restoration activities elicit feedbacks from individuals and groups that are harmed by restoration outcomes. They identify three potential outcomes ranked by the extent of restoration of ecosystem services and processes: nonstrategic, noncooperative strategic equilibrium, and cooperative bargaining solution. The authors apply their approach to restoration activities on California's upper Sacramento River.

Dinar et al. [2006] apply CGT as a mediated mechanism to water allocation in the Kat Basin in South Africa, where two groups of farmers and the environmental water flows compete against each other on scarce water. The GT approach is compared with a negotiated, role-playing game. Both approaches provide similar allocations among the two groups of farmers and the environment.

Supalla [2000] and Supalla et al. [2002] analyze the problem for the Middle Platte ecosystem, which arises from the insufficient water available to meet both instream ecological demands and out-of-stream economic needs. The game consists of a sequential auction with repeated bidding to determine how much instream-flow water each of three states — Colorado, Nebraska, and Wyoming — will provide and at what price. The results suggest that the use of auction mechanisms can improve the prospects for reaching a multi-state agreement on who will supply instream-flow water, if the auction is structured to discourage misrepresentation of costs and if political compensation is allowed.

Ji and Wang [2007] introduce voluntary environmental cooperation among regions in a river basin by means of Optimal Control Theory and GT, using cooperative and non-cooperative differential game models of water environmental management in a river basin. The authors derive a generalized formula of side-payment for promoting voluntary environmental cooperation among regions which is then applied to a water environmental management example in a simplified framework.

We conclude this section by mentioning three edited books [Hanley and Folmer, 1998, Dinar et al., 2008, Dinar and Rapoport, 2013] with many studies that apply GT to environmental issues, including water resources.

6.10 Watershed management and regulation/ river basin planning

The literature applying GT to watershed management could as well be placed in other sections such as international water (Section 6.7) or allocation (Section 6.6). However, we decided to select a subset of works that are characterized by introducing regulations and planning aspects to the basin/watershed analysis. The annual number of published works in this category is presented in Figure 6.10.

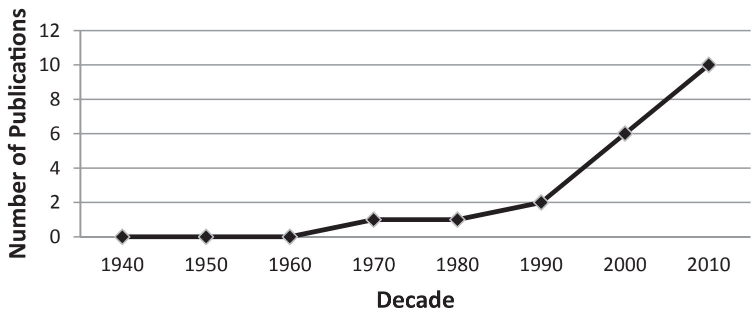

Figure 6.10: Annual GT publications, basin management, $N = 10$.

Collins and Maille [2011] develop two theoretical models that explain group allocation decisions at a watershed level including: rewards and penalty to individual contributors, and a reduced form problem with cost-sharing and joint abatement.

da Costa and Bottura [2007] present and use the Strategic Games Matrix (SGM) as a general framework for multiple interacting intelligent autonomous agents' control systems analysis and design that is inspired by GT. The SGM concept is applied to a water resources' regulation control problem, with multiple interacting autonomous stakeholders, in the watershed of Paijanne Lake in Finland.

Fernandez [2005] applies a game theoretic model of upstream and downstream countries in the Tijuana River watershed shared by the US and Mexico to examine cooperative and non-cooperative strategies of a common watershed management. The results suggest that different transfer payments, such as the Chander-Tulkens Cost-Sharing Rule or the Shapley Value, imply the size of the existing transfer from downstream to upstream could increase the amount currently allocated.

Hoffman [2010] examines the effort to protect the world's water supply by a cooperative institution of watershed collaboration, focusing on economic issues and using New York City's collaboration within the Catskill/Delaware watershed as a case study.

Howard [2006] interprets, using GT, how different participants behaved under certain sets of rules in 2000 when the New South Wales Government used a regional governance process to develop water management plans throughout the State. The work concludes by suggesting that GT is helpful in explaining stakeholder behavior.

Johnson et al. [1973] apply simulation games to planning in the context of a watershed. These games deal with prediction of different future consequences from alternative actions at present and the impact of the predicted consequences on the players. The game models a traditional life cycle of migrating tribes of Southern Sudan.

Okada et al. [1998] analyze the development of a regional water distribution system in a game that is characterized by two properties, namely, physical and social networks. Both the physical and social networks affect the cost functions. One interesting finding is that economies of scale may not always hold for water distribution pipeline systems. The notions of equilibrium based on Myerson's value coupled with "component balance" and "equal bargaining power" are proved to serve as the intended cost allocation scheme.

Wei and Gnauck [2007] demonstrate the resolution of a conflict over water resources in the Hanjiang River Basin as non-cooperative and cooperative games. Wei et al. [2010] illustrate management of the conflict associated with the South-to-North Water Transfer Project on the Yang Tse in China. In particular, the authors refer to conflicts concerning water allocation and nitrogen reduction and involve two levels, including one main game with five players and four sub-games, each containing three sub-players.

Other works of interest include Mahjouri and Ardestani [2011] who developed cooperative and non-cooperative methodologies for a large-scale watershed allocation problem (quantity and quality) in Southern Iran; Lee [2012] focuses on the development of a multi-objective game-theory model (MOGM) for balancing economic and environmental concerns in reservoir watershed management and for assistance in decision making, applying the framework to Tseng-Wen Reservoir, Taiwan.

6.11 Multipurpose water projects

The reader is referred to Section 2.1 for early application of GT to multiple water projects in the TVA. Besides that early literature we

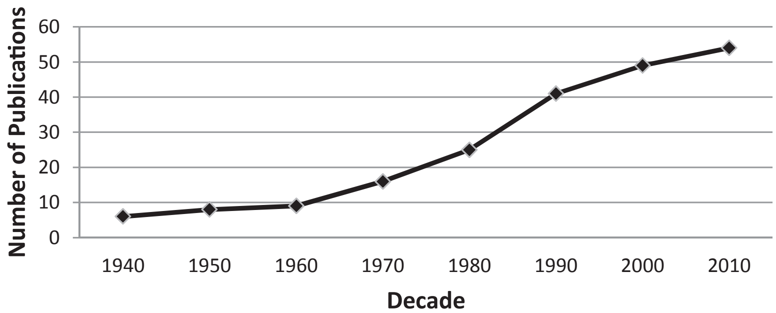

Figure 6.11: Annual GT publications, multipurpose, $N = 54$.

report in this section additional and recent works. The works in this category refer to different sectors that are involved in a multipurpose project such as a dam, a reservoir, or a water supply project. The major question these works address is the allocation of benefits and costs among the sectors involved in the project. The annual number of published works in this category is presented in Figure 6.11.

Driessen and Tijs [1985] compare four different cost allocation methods for joint costs of water resource projects among sub-projects, based on separable and nonseparable costs. Three non-GT methods: the Egalitarian Nonseparable Cost (ENSC) Method, the Separable Costs Remaining Benefits (SCRB) Method, the Minimum Costs Remaining Savings Method, and a new method, the so-called Nonseparable Cost Gap Method, based on the GT γ-value. The non-GT methods do not necessarily belong to the Core.

Straffin and Heaney [1981] consider the fair allocation of joint costs in relation to dividing costs of dam systems among participatory uses. The authors apply solution concepts including the Core, a special case of the Nucleolus and the imputation which minimizes the maximum propensity to disrupt.

Homayoun-Far et al. [2010] develop a continuous model of dynamic game of reservoir operation when demands from various uses exist. The authors use two solution concepts: the Ricatti Equations and Collocation Methods. The Ricatti Equations Method is a closed-form solution, requiring less computational effort compared with discrete models. The collocation solution method applies Newton's Method or a quasi-Newton Method to find the problem solution. The two solution concepts were applied to a reservoir in the Zayandeh-Rud River Basin in central Iran as a case study and the results are compared with alternative water-allocation models. The results show that the Collocation Method leads to improved values of the reliability indices for the total reservoir system and utility satisfaction of water users, compared to the Ricatti Equation Method. Homayoun-Far et al. [2011] further develop the model by considering a stochastic dynamic game for water allocation from a reservoir system. The continuous random variable of inflow to the reservoir in the state transition function was replaced with a discrete approximation rather than using the mean of the random variable. The Collocation Method was introduced as an alternative to Linear-Quadratic (LQ) approximation methods to resolve a dynamic model of game.

In their book chapter, Dinar et al. [2006b] develop a simple model that incorporates the stochastic nature of water supply to a regional model to determine the size a regional water project under stochastic water supply. In view of future climate change effects on the water cycle, the world is expected to face more stochastic and extreme events of water supply. Therefore, incorporating stochastic consideration of water supply becomes more acute in designing regional water facilities. With various water users having different attitudes toward risk, the combination of stochastic events and players' risk attitude becomes increasingly important in regional cooperation. The authors apply a Stochastic GT framework to an example of a water treatment plant.

Israel et al. [1994] present a very general GT framework for reassessing the operation and management of existing multi-purpose water projects subject to competing and conflicting water uses, with application to the water use conflicts in the Truckee-Carson Basin, Nevada.

Loughlin [1977, 1978] examines the efficiency and equity of the SCRB allocation method in a multi-purpose water project allocation problem.

Okada [1982] and Okada and Tanimoto [1996] compare the results of the SCRB method to the Weak Nucleolus and to the Proportional Nucleolus in an allocation problem of the cost of a multi-purpose reservoir in two variations of the sectors involved.

And finally, Suttinon et al. [2012] demonstrate the use of option games to evaluate trade-offs between flexibility and strategic commitment in industrial water infrastructure projects. The approach combines real options and game theory. It was applied to the case of the Government of Thailand's investments in tap and industrial water supplies and/or the private sector investment in recycled-water development. The investments are evaluated under four different strategic scenarios: (1) both parties invest, (2) Government invests first, private sector waits, (3) private sector invests first and Government waits, and (4) both parties wait. Results suggest that option games provide a tool that allows decision makers to accurately value all choices with consideration not only of future uncertainties, but also of competitors' decisions.

7

Conclusions and Further Needs in the Field of Water

Game Theory applications and developments for water resources have shown a significant increase in the past seven decades. We reviewed the use of GT approaches in various water resource sectors from 1942 to 2013. We were able to identify and catalogue nearly 600 works that use and apply GT concepts and frameworks to water resource management. However, about half of these works were, in our opinion, less appropriate to be used in this paper because of their very stylistic nature — highly abstract water systems that cannot be extrapolated to other locations or circumstances. The remaining 294 works we analyzed in the paper allowed us to create a comprehensive set on water issues and the success or difficulties of applying GT to address these issues.

Clearly, GT can be a very good tool in addressing certain issues, but may face difficulties with other issues. In the following, we review major strengths realized in the field and future developments that are needed in our opinion.

The scope and intensity of GT works for allocation of joint water project costs have been very impressive. Cooperative Game Theory allocation schemes have led many, if not the majority, of water projects over several decades and continue leading that work to date. Allocation schemes have been successfully applied at local, regional, and international levels, at sectoral and multisectoral levels, and in a variety of projects with different natures. However, we observe rather a small group of works that apply GT to water-related issues that are characterized by externalities and/or stochastic nature in supply. These two aspects — externality and stochasticity — are rather important in the future development of the water sector due to increased competition over scarce water resources, leading to different negative externalities, and due to the impact of climate change, leading to the increased stochastic nature of water supply.

GT made also, especially in recent years, a major contribution in the field of international water. This is actually the field with the highest increase in GT applications, which is not surprising, given the strategic nature of international scarce water that are shared by riparian states with increasing populations. Works, employing GT approaches, made their mark both in issues related to allocation of the water or the benefits from water uses among the riparians, and in issues related to regulation of transboundary unidirectional externalities (pollution). However, like in the case of cost allocation for joint projects, GT so far did not properly or widely enough address the issues of externalities and stochasticity in the supply of the water to the flow of the basin. This is a bit surprising since, especially in the field of international water, other categories have moved forward with advanced applications of methods and examples addressing unidirectional externalities and stochasticity.

One of the major problems facing water sector management and planning decision is the impact of climate change on water supply and its effect on decisions leading to permanent infrastructure investment. While we reviewed several works that applied stochastic cooperative game theory approaches, it appears that much more is needed in light of the likely increase in water variability due to climate change.

We also realized that the role of GT in multi-party negotiations and allocations could be enhanced in works with issue linkage framework. Issue linkage allows the players involved to expand the core, such that solutions to an issue at dispute may have higher likelihood of being agreed on. Expanding the game by adding issues to the negotiating matrix is one possibility of arriving at a stable solution. Another possibility is to expand the group of players beyond the original set by searching and adding more members to the set that may lead to a higher likelihood of cooperation. Indeed one has to consider the higher transaction costs associated with larger group of players, which may make it less desirable to expand the set of players. But, given the high rate of economies of scale in joint facilities, this is a risk worth taking.

Finally, we have seen very little attention placed on the important aspect of equity in the hundreds of papers we reviewed. The angle of equity is critical in the stage of evaluating the stability of the solution to the game. While the traditional assumption of profit maximization holds in most works reviewed, it is still not sufficient in dealing with situations where there is a large range of welfare differences between the various players involved. Having very rich and very poor players in the same game (e.g., international games, regional games, urban games) leads to results that will not be acceptable to some players, even if traditional game theory acceptability and stability conditions (such as Core) hold.

Acknowledgements

We would like to thank Getachew Nigatu for help in the early stages of the data collection process and to Bill Hogarth for help in the production of the various graphs in the manuscript. We benefitted from comments provided by Georges Zaccour, Daene C. McKinney, and an anonymous journal reviewer. Ariel Dinar would like to acknowledge the support provided at the stage of finalizing the manuscript from the Department of Environmental Economics and Management at the Hebrew University of Jerusalem while on sabbatical leave at this institution. Funding from the Lady Davis Trust and the Center for Agricultural Economic Research are greatly appreciated.

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Annex 1. Data Collection and Classification Methodology

We reviewed literature in several subscription databases, including EconLit, Web of Science, Compendex, PAIS International, Worldwide Political Science Abstracts, and CIAO. GoogleScholar was also used. EconLit collects scholarly economic and related literature from 1969 to present, covering accounting, consumer economics, monetary policy, labor, marketing, demographics, modeling, economic theory, planning, and more. Web of Science indexes scholarly literature in the sciences, social sciences, arts, and humanities. For the purposes of this review, sciences from 1900 to present and social sciences from 1956 to present are compiled and searched. Compendex comprehensively catalogs engineering literature. In addition to economic issues, PAIS (Public Affairs Information Service) International lists selected literature on politics, business, finance, law, international trade and relations, public administration, government, political science, public policy, and social issues from 1972 to present. Worldwide Political Science Abstracts focuses on political science and government articles from 1984 to present. Columbia International Affairs Online (CIAO) covers working papers from university research institutes, papers series from NGOs, foundation-funded research projects, and proceedings from conferences from 1991 to present. In order to reduce massive numbers of results, GoogleScholar can be adjusted to include a library's holdings in an OpenURL Linker, which enables discovery and access to the university's subscribed resources.

Indexers categorize works in a database using the database's controlled vocabulary of index terms, subjects, and/or descriptors. Additionally, authors may supply keywords. The databases may be produced by different publishers and may use distinctive descriptors, subjects, or indexing terms to describe similar ideas. Initial suggested keywords used for our search include cooperative/non-cooperative game theory, water, hydropower, irrigation, environment, pollution, wastewater, rivers, international waters, water ways, urban/residential water, developing countries, developed countries, equitable allocation, poverty, flooding, drought, equity, natural resources, aquifers, and transboundary waters. Fisheries are not covered in this monograph.

Exploratory keyword searches in each database using terms such as "game theory" and "water" or "environment" allow us to discover what the actual descriptors or subjects for the research are for each database. For example, a search in EconLit for keywords "game theory" and "water" might show the following subjects (followed by the number of citations in the database):

- Economic development: agriculture; natural resources; energy; environment; other primary products (18)
- Game theory and bargaining theory: general (43)
- Game theory and bargaining theory: other (21)
- Renewable resources and conservation: government policy (14)
- Noncooperative games (12)
- Renewable resources and conservation: water (56)
- Air pollution; water pollution; noise; hazardous waste; solid waste; recycling (21)
- Cooperative games (17)

A similar keyword search in Compendex might yield:

- Game theory (142)
- Water resources (36)
- Mathematical models (34)
- Resource allocation (25)
- Decision making (23)
- Algorithms (22)
- Optimization (22)
- Probability — game theory (22)
- Decision theory (17)
- Iterative methods (16)

A Web of Science query with the same keywords might result in:

- Water resources (58)
- Environmental Sciences (51)
- Engineering electrical electronic (46)
- Engineering civil (40)
- Economics (28)

The scope, vocabularies, and search algorithms of the databases differ, dramatically affecting the results. Even with refinement of subject terms, the citations needed to be extensively reviewed for relevancy. Phrases might be enclosed in quotes in order to force exact matching. Boolean logic could be employed to be sure that multiple terms were present in the search results by using the operator "AND" with subject terms. The operator "NOT" could be employed to force exclusion of any topic such as fisheries. As time passed during the project, searches could be modified to exclude citations from the past as those had already been "found." Additionally, a database might supply clickable facets, so that one can limit results by source type (journals, papers, books, book chapters, dissertations, etc.), year, subject terms, or publication. Late in the project several new, older citations were discovered as new resources were indexed by the database providers, particularly in Web of Science.

We started with an initial set of 103 citations, which formed the foundational set of citations in EndNote Web. Searches were performed periodically over a three-year period gathering over 600 citations. Most of the rest of the citations were found in the EconLit and Web of Science databases. Citations were entered into EndNote Web in labeled sets, usually the database name and the date, using automated importing features provided by the databases wherever possible. Some databases have better functioning export abilities into citation management tools. To populate records in EndNote Web, as many fields as possible were filled in the record, including abstracts, subjects, keywords, and OpenURL links. In some cases, additional fields or even entire records were added by hand. New citations were reviewed and placed into working sets in EndNote Web; they were labeled "Include," "Maybe" and "Exclude." Over time, as each database was reviewed for new citations, it became necessary to check the list of potential citations against the existing sets in EndNote Web to avoid duplication. The set name was entered into the Research Note field. If the citation was in print and owned by the university libraries, then the library, catalog record link and call number were noted. If the item needed to be requested by interlibrary loan, it was noted and the item requested.

Working collaboratively online from two different institutions presents some logistical wrinkles to work out. At one point it became necessary to move sets from one account to another, changing the owner to the data set. Not wanting to lose any data, sets were named Include, Include_old, Exclude, and Exclude_old. At the time of writing, using Cite While You Write in Microsoft Word, it can be confusing which citation is the "right" citation to insert, as the citation from each set will show multiple times in the drop-down list. It became clear that unique identifying words were needed to distinguish which citation was the "correct" citation from the correct set. Phrases such as "Final Include" were added to the Include set. At the point of insertion, using Cite While You Write, it was fairly simple to scroll down through the record and find the appropriate phrase and insert the correct citation. Since Cite While You Write builds the reference list as citations were inserted, choosing the correct citation means there will not be any duplicate citations in the reference list.

Citation management software saves time, effort and allows better organization during the research and writing process. However, clean data can be a seemingly insurmountable goal. Even with the utmost care, dirty data crept into the data set. Surprisingly, sometimes the database indexers got it wrong. The database citation exporter may garble the data, or human error might sneak into hand-entered data. One database might include an initial, the other the first name. First and last names may be transposed. Lead authors might change. Deduplication was done regularly in multiple waves. Transposed names were not discovered until later and required backing up to fix fundamental problems in the data set. Some exported citations, perhaps from different databases, contained more fields of information than others, requiring comparison and filling in.

A matrix was created to help analyze, formulate trends in the data and determine subheadings. A spreadsheet was created where each citation in the dataset was both a row heading and a column label. In the intersecting cell, keywords and subjects were listed. Keywords and subjects were then experimentally run through a freely available text analyzer. After gathering the keywords and subjects, they were cleaned and processed into a spreadsheet and submitted into the online tool. The results (Table A.1) were not very helpful as individual words, not phrases, were reported.

To prepare for the writing, citations were categorized into the following categories for annual and cumulative game theory citations: urban water, hydrology, irrigation, pollution, groundwater, allocation, international water, negotiation, ecology, basin management, and

Table A.1: Text analyzer results by word frequency and rank.

Word	Occurrences	Frequency (%)	Rank
Water	346	6.20	1
Game	191	3.40	2
Theory	181	3.20	3
Resources	143	2.50	4
Management	112	2.00	5
Resources	108	1.90	6
Theory	96	1.70	7
Renewable	87	1.50	8
Conservation	87	1.50	8
Decision	77	1.40	9

multipurpose. Citations were limited to one topic for the categorization. Additionally, citations were grouped into sections covering the history, trends, and the future of game theory. Once arranged in logical order, abstracts were inserted. Data set quality remains a constant concern. It is important to make sure the final set of citations contains all of the citations needed for the review. Citations may need to be moved into or out of the final set. A spreadsheet was constructed showing the section, subsection, author, year of publication, and any required notes such as a few words from the abstract in order to identify the author's different citations from the same year. This spreadsheet could also be used to prepare the pivot tables for the publication trend lines for each subsection of the paper.

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