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Cooperative water management and ecosystem protection under scarcity and drought in arid and semiarid regions

Mohamed Taher Kahil [a], Ariel Dinar [b], Jose Albiac [a,*]

[a] Department of Agricultural Economics, CITA-Government of Aragon, Zaragoza, Spain
[b] School of Public Policy, University of California, Riverside, CA, USA

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ABSTRACT

Climate change impacts and the growing concern on environmental water demand are further increasing competition for scarce water resources in many arid and semiarid regions worldwide. Under these circumstances, new water allocation mechanisms based on the involvement of stakeholders are needed, for an efficient and fair allocation of water and income among users. This paper develops a cooperative game theory framework in order to analyze water management policies that could address scarcity and drought in a typical arid and semiarid basin in Southeastern Spain. The results provide clear evidence that achieving cooperation reduces drought damage costs. However, cooperation may have to be regulated by public agencies, such as a basin authority, when scarcity is very high, in order to protect ecosystems and maintain economic benefits. The cooperative game theory solutions and stability indexes examined in this paper demonstrate the importance of incorporating the strategic behavior of water stakeholders in the design of acceptable and stable basin-wide drought mitigation policies.

1. Introduction

Global water resources are under increasing pressures that create growing water scarcity and quality problems, giving rise to complex social conflicts and environmental degradation. Water extractions across the world have increased more than six fold in the last century, much above the rate of population growth [1]. It is estimated that about 35% of the world population suffers from severe water stress and about 65% of global river flows and aquatic ecosystems are under moderate to high threats of degradation [2,3].

Water scarcity has become widespread in most arid and semiarid regions, including river basins such as the Yellow, Jordan, Murray-Darling, Colorado, and Rio Grande [1,4]. Projected future climate change impacts would further exacerbate the current situation of water scarcity in arid and semiarid regions. These regions would likely suffer a decrease in water resources availability and experience longer, more severe, and frequent droughts [5].

Emerging social demands for environmental protection in the form of secured minimum flows for water-dependent ecosystems further increase competition for already scarce water in arid and semiarid regions, especially during dry years. Water-dependent ecosystems, such as wetlands, provide a diverse range of goods and services to society, including habitat for valuable species, flood control, groundwater replenishment, water quality improvement, waste disposal, and recreational opportunities [6]. However, water-dependent ecosystem services are

* Correspondence to: Department of Agricultural Economics, CITA-DGA, Avenida Montañana 930, 50059 Zaragoza, Spain.
Fax: +34 976716335.
E-mail addresses: mt.kahil@gmail.com (M.T. Kahil), adinar@ucr.edu (A. Dinar), maella@unizar.es (J. Albiac).

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external to markets, and their social values are overlooked in water allocation decisions. For instance, an estimated 50% of world wetlands have disappeared over the last century [7].

Several policy responses have been suggested to cope with water scarcity and to mitigate the negative impacts of droughts for the different water use sectors. These policies include reducing water allocations, water transfers, conjunctive use of ground and surface waters, groundwater banking, recycling and reuse of wastewater, seawater desalination, improving water use efficiency, adopting water conserving-technologies, changing crop mix, setting minimum environmental flows, and implementing economic instruments such as water pricing and water trade including water purchases for environmental purposes.

These policy alternatives have been previously analyzed in several studies such as Booker et al. [8]; Howitt et al. [9]; Kirby et al. [10]; and Zilberman et al. [11]. However, the existing literature, while assessing solutions to drought situations using engineering, economic and institutional approaches, usually overlooks one important aspect, which is the strategic behavior of individual stakeholders. The analysis of the strategic behavior of stakeholders is essential for testing the acceptability and stability of policy interventions aimed at basin-wide drought mitigation.

This gap is addressed in this paper by developing a cooperative game theory (CGT) framework in order to analyze water management policies aimed to deal with scarcity and drought at a basin scale. The paper contributes to the literature on water policy through the inclusion of the strategic behavior of various stakeholders and the ecosystem benefits in the river water management problem. Several CGT solution concepts and stability indexes are used to find efficient and fair allocations of water and income among river water users under various climate scenarios. In addition, the analysis considers the likelihood of succeeding in ecosystem protection.

The CGT deals with games in which stakeholders (players) choose to cooperate by forming coalitions and sharing fairly the benefits from those coalitional arrangements. In particular, CGT favors agreements that include all possible players (grand coalition) and it provides several benefit sharing mechanisms (solution concepts) based on different notions of fairness. The purpose is to find the incentives for cooperation among stakeholders in order to achieve economic efficient outcomes for the coalitions. The advantage of using CGT compared to conventional optimization models is its ability to address both efficiency and equity principles, which would promote acceptable and stable cooperative outcomes [12]. CGT models were developed and have been applied to various aspects of water management in the literature, such as decisions on cost and benefit allocation in multipurpose water projects, efficient sharing of river systems, joint management of groundwater aquifers, optimal operation of hydropower facilities, and resolution of transboundary water conflicts [13–15].

The CGT framework is applied to the Jucar River Basin (JRB) of Spain, which is a good case for studying the strategic behavior of stakeholders and policies to confront water scarcity and drought impacts from the impending climate change. The JRB region is semiarid and the river is under severe stress with acute water scarcity problems and escalating degradation of ecosystems. Another interesting aspect of the JRB is that there have been already successful policies leading to stakeholders' cooperation. In particular, the curtailment of water extractions in the Eastern La Mancha aquifer that were threatening the activities of downstream stakeholders [16].

2. Cooperative game theory framework

This section presents the CGT framework used to analyze water management policies addressing scarcity and drought at basin scale. Assume that a basin includes $n > 1$ users (players in the game). The users consider a cooperative management of the basin by agreeing to share water resources. Initially, the users have predetermined administrative water allocations depending on the climate condition. Under the cooperative water sharing agreement, the agency responsible for water allocation reallocates water among uses so that the whole basin benefits are maximized. When additional benefits are obtained through this cooperative agreement compared to non-cooperation (status quo), the water agency needs to distribute these benefits among the cooperating users in a fair way that would sustain cooperation.

Let N be the set of all players in the game, S is the set of all feasible coalitions, and s ($s \in S$) is one feasible coalition. The singleton coalitions are $\{l\}$, $l = 1,2,\ldots, n$, and the grand coalition is $\{N\}$. Assume that the objective of the water agency is to maximize the benefits, f^s, of any feasible coalition in the basin, s, by efficiently allocating water among the players in that coalition. Let $\nu(s)$ be the characteristic function of coalition s, which is the best value that such coalition can obtain. The cooperative water sharing agreement takes the following form:

$$\nu(s) = Max\, f^s = \sum_{l \in s} B_l \tag{1}$$

subject to

$$\sum_{l \in s} WU_l \le WA_s \tag{2}$$

where B_l is the private net benefits from water use of player l in coalition s. The water constraint (2) states that the sum over players, l, in coalition, s, of water use by each player, WU_l, must be less than or equal to water available for that coalition, WA_s.

When additional benefits are obtained through this cooperative agreement compared to non-cooperation, the water agency overseeing the agreement needs to allocate these benefits among the cooperating players in a fair way in order to secure the acceptability and stability of the agreement. These allocations could be determined using the CGT solution concepts. A necessary condition for cooperation in the basin is that the benefits obtained by each