WATER RESOURCES MANAGEMENT IN THE RIO GRANDE/ BRAVO RIVER BASIN USING COOPERATIVE GAME THEORY

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Water resource management is a multifaceted issue that becomes more complex when considering multiple nations' interdependence upon a single shared transboundary river basin. With over 200 transboundary river basins worldwide shared by two or more countries (Wolf, 2002), it is important to develop tools to allow riparian countries to cooperatively manage these shared and often limited water resources. Cooperative game theory provides tools for determining if cooperation can exist across jurisdictional boundaries through a suite of mathematical tools that measure the benefits of cooperation among basin stakeholders. Cooperative game theory is also a useful for transboundary negotiations because it provides a range of solutions which will satisfy all players in the game and provides methods to fairly and equitably allocate the gains of that cooperation to all participating stakeholders, if that cooperation is shown to be possible.

A large body of literature outlines cooperative game theory applications in water resources management. However, there is limited work on the application of cooperative game theory to transboundary river basins. Cooperative game theory has been applied to water sharing in the Ganges and Brahmaputra basin (Rogers, 1969; Rogers, 1993), the Nile basin (Wu and Whittington, 2006; Wu, 2000), and Euphrates and Tigris (Kucukmehmetoglu and Guldmann, 2004; Kucukmehmetoglu, 2002) basins and for water trading from the Nile among the Middle East countries of Egypt and Israel, and the Gaza Strip and the West bank (Dinar and Wolf, 1994). In each of these cases, the individual countries were considered as the players in the game. For this research cooperative game theory concepts are applied to the water scarce transboundary Rio Grande/Bravo basin in North America. Unlike the previous studies, this application specifies individual water users in the basin (*i.e.* irrigators, municipalities, etc) as the players in the game which will obtain any increased benefits from cooperation. Additionally, the literature has shown that the water planning models utilized in transboundary cooperative games tend to be oversimplified or lack accurate data and there has been little inclusion of politics into transboundary cooperative games. This research aims to develop a model with accurate data that follows the constraints of the international treaties governing the basin. A detailed water planning model coupled with cooperative game theory concepts will provide the stakeholders in the Rio Grande/Bravo basin with a powerful tool for quantifying the value of cooperating to improve water management in the entire basin.

The Rio Grande, or Río Bravo del Norte as it is known in Mexico, is home to over 10 million people and is considered to be one of the most water stressed basins in the world (WWF, 2007). Rapid population growth and economic development have placed additional strain on already limited water resources of the basin. This transboundary basin has increased complexity due to its large size. The river is 3,107 km from its headwaters in the mountains of southern Colorado in the United States to the Gulf of Mexico. The Rio Grande/Bravo flows through the three U.S. states of Colorado, New Mexico and Texas and the four Mexican states of Chihuahua, Coahuila, Nuevo Leon and Tamaulipas. Additionally, the river forms over 2,000 km of international border between Mexico and the United States (Patino *et al*., 2007).

To satisfy water management objectives for the Rio Grande/Bravo while meeting current needs in all sectors, all segments, and in both nations, a water resources planning model has been developed to analyze the opportunities for improved water management. The Physical Assessment project is a collaborative effort between technical and expert counterparts in Mexico and the U.S. and is aimed at improving management of the scarce water resources of the river through development and modeling of management scenarios. The management scenarios fall within the current water allocation structure in the basin including treaties, compacts, and water rights. Commons ideas emerging for the stakeholder driven scenarios include groundwater banking, transferring conserved water to municipalities, retiring water rights, re-operation of reservoirs to increase water availability and even establishing environmental flows. At this time, scenarios have been modeled for groundwater banking and water right retiring. Environmental flows will be considered in the future. To model the scenarios a hydrologic planning model was developed to evaluate the management scenarios for both physical feasibility and the ability to provide mutual benefits to stakeholders in the basin.

Developed with the software WEAP (Water Evaluation and Planning), the hydrologic planning model is a demand driven model containing hydrologic and hydraulic data for 60 years as well as water rights and logic for the legal institutions in the basin including international treaties, interstate compacts and allocation rules. This model will be used with the scenarios to demonstrate the effects of management changes on water availability in the basin. Cooperative game theory concepts will be applied to these scenarios by identifying players who are able to form binding agreements, or coalitions, with other players. These coalitions range from non-cooperative coalitions where players act to maximize their benefits, to full cooperative coalitions where all players act collectively to maximize the coalitions' benefit beyond the non-cooperative solutions. Partial coalitions, or subsets of players, may also form. The model will be used to calculate the value, or characteristic function, of these coalitions. From these characteristic functions, the core is calculated. The core is a set of allocations which improve the standing of all players in a coalition. Allocation concepts, such as the Shapley value, allocate gains to players. Cooperative game theory can demonstrate if there are increased benefits to all basin stakeholders through cooperation.

To illustrate the cooperative game theory application, a ground water banking game is described. Groundwater banking is achieved through a method called *In Lieu* banking where surface water is used to meet water demands when available surface water is above a certain threshold. Goroundwater is then allowed to recharge without pumping. When surface water availability falls, groundwater is then pumped to meet demands (Sandoval-Solis *et al*., 2008). In this game, three players considered; Player 1 is Mexican Irrigation District 005, Player 2 is the Below Falcon U.S. Irrigation Districts and Player 3 is Mexican Irrigation District 025. For this game the characteristic functions were calculated by running the Rio Grande/Bravo WEAP model for the first 5 years of the record drought for the region (1947-1951) to represent a water scarce period and the average annual delivery volumes were determined in millions m^3 (MCM) (Table 1). The incremental gains from the historical run were considered to be the benefit. The characteristic function for the non-cooperative coalitions are equal to zero because this represents the historical conditions.

Table 1 Characteristic Values of the Groundwater Banking Game

Coalition Type	Players in Coalitions	Characteristic Value (MCM)
Non-cooperative	1	0
Non-cooperative	2	0
Non-cooperative	3	0
Partial Cooperation	1,2	22
Partial Cooperation	1,3	53
Partial Cooperation	2,3	0
Full Cooperation	1,2,3	63

The core is determined from the characteristic functions (Figure 1). The core represents the feasible allocations to the individual players. The Shapely value calculates a single allocation from the core. For this game the Shapley value allocated 34 MCM to Player 1, 7 MCM to Player 2 and 23 MCM to Player 3. Under the non-cooperative conditions, the players did not receive an increased benefit and their characteristic values are equal to zero (Table 1).

The Shapley value allocations demonstrate that there is an increase in benefit to all the players in the game through cooperation.

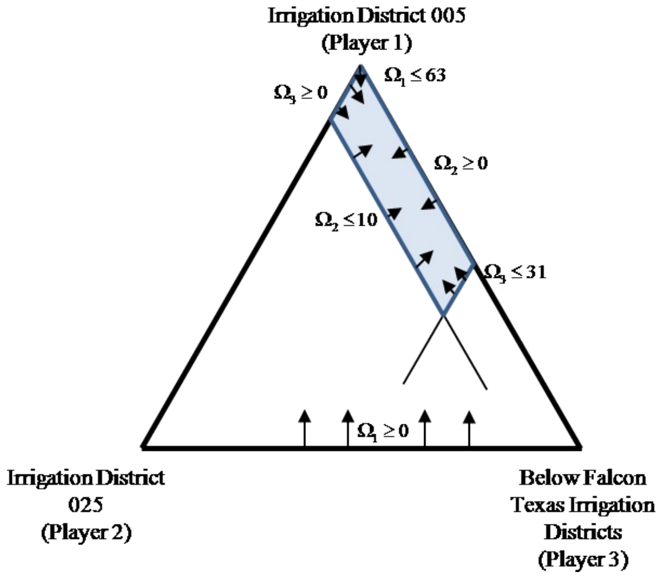

Figure 1 Core of the Groundwater Banking Cooperative Game

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