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Evaluating Water Resource Management in Transboundary River Basins using Cooperative Game Theory: The Rio Grande/Bravo Basin

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Evaluating Water Resource Management in Transboundary River Basins using Cooperative Game Theory: The Rio Grande/Bravo Basin

by

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Dissertation

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

The University of Texas at Austin
August, 2009

Dedication

I dedicate this dissertation to my husband and my family for their love and support

Acknowledgements

I would like to express my gratitude to my advisor Dr. Daene McKinney for his guidance and support throughout my time at The University of Texas. Dr. Mckinney provided me with the opportunity to delve into the fascinating field of international water management and allowed me to work on some great projects. I would like to thank Dr. Randall Charbeneau, Dr. David Maidment, Dr. Charles Groat and Dr. David Eaton for being members of my dissertation committee and for their kind words of encouragement along the way. Their helpful comments and insight helped pull this dissertation together.

Special thanks to Dr. Carlos Patino-Gomez for sharing his vast knowledge of the Rio Grande/Bravo basin with me over the years. I also really appreciate his friendship and getting to travel the world with him. Samuel Sandoval-Solis has provided an amazing amount of support with expertise in scenario modeling. He has become a great friend over the last few years and I am thankful for all of your support and friendship. All of the support staff at CRWR, including Sharon Bernard, Marcy Betak and Susan Swanson-Cartright, has helped me to successfully navigate the world of graduate research assistants.

Funding for this research was provided through the U.S. EPA and USDA as part of the Physical Assessment Project. I would like express my gratitude to the various

project partners that I have met over the years in the U.S. and Mexico, who each added to my research in some way. I would also like to thank Dr. Ariel Dinar for his helpful insight in the beginning stages of my cooperative game theory understanding.

I have had an amazing support group through the friends that I have made at UT. I am grateful for my friends Jessica Watts, Paula Kulis, Shipeng Fu, Lily Chen, Mara London, Susan DeLong, Nate and Rebekah Johnson, Eric Hersh, various CRWR students throughout the years, and all of my geotech friends. I especially want to thank Pam Kearfott for being a great friend and a great supporters in my academic and personal pursuits;Suzanne Pierce for her infectious enthusiasm and friendship; and Alicia Fogg, Ken Siefken, Lauren Starosta and Matt Starosta for many evenings sitting in Ken's driveway which made our time in Austin a little more fun. To Chris Buono, aka "The Minion," thank you for all of you hard work.

I thank my parents for never pushing, and always encouraging me to do the best that I can in everything I do. They have supported me over the past 30 years and I would not be where I am today without them. Thank you for doing so much for me, including reading my dissertation. Words cannot express how grateful I am to have you as my parents. Finally, I would like to thank my husband for supporting me through my doctoral program. He has provided helpful feedback and excellent editing on my work. I am especially grateful to have a partner who is allowing me to pursue my career goals and has followed me from California to Texas and then to New Zealand.

Evaluating Water Resource Management in Transboundary River Basins using Cooperative Game Theory: The Rio Grande/Bravo Basin

Publication No._____________

Rebecca Lynn Teasley, Ph.D.
The University of Texas at Austin, 2009

Supervisor: Daene C. McKinney

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, 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 useful for transboundary negotiation 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. This dissertation applies cooperative game theory concepts to the Rio Grande/Bravo basin in North

America as a case study. The Rio Grande/Bravo forms the 1,200 km border between the United States and Mexico. A comprehensive water resources planning model was developed for the basin including the major water users, water related infrastructure including reservoirs, and water policy logic related to the bi-national water sharing agreements. The water planning model is used to calculate the characteristic functions for the cooperative game analysis. For the Water Demand Reduction Game, the largest agricultural users, District 005, District 025 and the Texas Watermaster Section below Falcon were defined individual players. The cooperative analysis was between the individual players rather than the countries. In addition to the cooperative analysis, performance measures for water deliveries were calculated to determine if water delivery was improved to each player under the cooperative game. The results show that the amount of additional water to the downstream players may not be large enough to induce cooperation. The small amount of increase in water deliveries is related to the large system losses as the water travels downstream over a long distance and a division of water under the 1944 Treaty between the United States and Mexico.

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1 INTRODUCTION

Water resources management is a complex and varied topic. Population growth and economic development place added demands on limited water resources. Transboundary river basins, or basins that are shared by two or more countries, add complexity to water management. These basins are subject to laws and regulations of all countries that they flow through rather than just a single country. More than 200 river basins around the world have been identified as being shared by two or more countries (Wolf, 2002).

Conflicts arise in transboundary river basins when asymmetries exist with respect to information, power, or location (Just and Netanyahu, 1998). Asymmetric information arises when riparian countries (countries sharing a transboundary basin) have differing access to and quality of data regarding a basin. Asymmetric power can be related to either wealth or military power. Usually, power asymmetry allows some riparian countries to develop more water projects, such as reservoirs or irrigation systems, than other riparian countries (Just and Netanyahu, 1998). Location asymmetry refers to upstream - downstream geographic location of riparian users in a basin. All of these asymmetries allow some countries to have strategic power over other countries in water negotiations within a basin (Just and Netanyahu, 1998).

To overcome asymmetries among riparian countries and improve the management of water resources, researchers have applied cooperative game theory to this problem. Cooperative game theory provides tools for determining if cooperation can exist in a basin through a suite of mathematical tools that measure the benefits of cooperation among basin stakeholders (and across jurisdictional boundaries in the research considered here). Cooperative game theory also provides methods to calculate fair and equitable allocations of cooperative gains to stakeholders if the cooperation is possible.

To determine the possible benefits of cooperation among riparian users in a river basin, water planning models can be very helpful. Often these models are simplified with emphasis placed on the game theory calculations. However, coupling the game theory calculations with a comprehensive, and rather detailed, water planning model may increase the reliability of the outcomes. Many models exist for the hydraulics and hydrology of river basins. These models are powerful tools, which when used appropriately allow more informed decisions regarding river basin management. Models can be used for reservoir operations, water availability forecasting, water allocation, flood modeling, and even environmental restoration. Using a comprehensive river basin model with cooperative game theory can give transboundary river basin stakeholders a powerful tool for negotiation and increasing basin-wide benefits.

1.1 Background

The Rio Grande has been selected as a study basin for the application of cooperative game theory concepts to a transboundary basin. The Rio Grande, or Río Bravo del Norte as it is known in Mexico, is the fifth longest river in North America flowing 3,107 km from its headwaters in the San Juan Mountains of southern Colorado to the Gulf of Mexico. The Rio Grande/Bravo flows through the Chihuahuan Desert, which is the largest desert in North America (Figure 1-1). The river 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. Upon entering Texas from New

Mexico near El Paso, the river forms over 2,000 km of international border between Mexico and the United States (Patino *et al*., 2007). The river will be referred to throughout this document as the Rio Grande/Bravo.

The Rio Grande/Bravo basin is home to over 10 million people (WWF, 2007). Currently municipal demands account for only 11% of the total surface water demands in the basin, while irrigation accounts for 88% of these same demands. Mexico irrigates approximately 4,800 km^2 in the basin (CNA, 2003), while the United States irrigates about 4,020 km^2 (The Alliance for the Rio Grande Heritage *et al*., 2000). Of the 4,020 km^2 irrigated in the Rio Grande/Bravo basin in the U.S., only about 400 km^2 lie upstream from Texas in New Mexico and Colorado (The Alliance for the Rio Grande Heritage *et al*., 2000).

The United States and Mexico have two major legal agreements for sharing the waters of the Rio Grande/Bravo. These agreements are the 1906 Convention (IBWC, 1906) and the 1944 Treaty (IBWC, 1944). The 1906 Convention for the "Equitable Distribution of the Waters of the Rio Grande" deals with dividing the waters of the Rio Grande/Bravo above Ft. Quitman, Texas for irrigation purposes (IBWC, 1906). Under the 1906 Convention, Mexico agreed to the construction of Elephant Butte Reservoir in New Mexico and the U.S. guaranteed Mexico a total delivery of 74 million cubic meters (MCM) of water annually. This water is delivered according to a monthly schedule, outlined in the 1906 Convention, through the Acequia Madre canal near Ciudad Juarez, Mexico. The U.S. completed construction of Elephant Butte Reservoir in 1916 to ensure the scheduled deliveries to Mexico as well as to provide for their own irrigation demands.

The 1906 Convention contains a provision stating that in event of drought, the water deliveries to Mexico may be reduced in the same proportion as reduced deliveries to the U.S. in the stretch of the river near El Paso (IBWC, 1906).

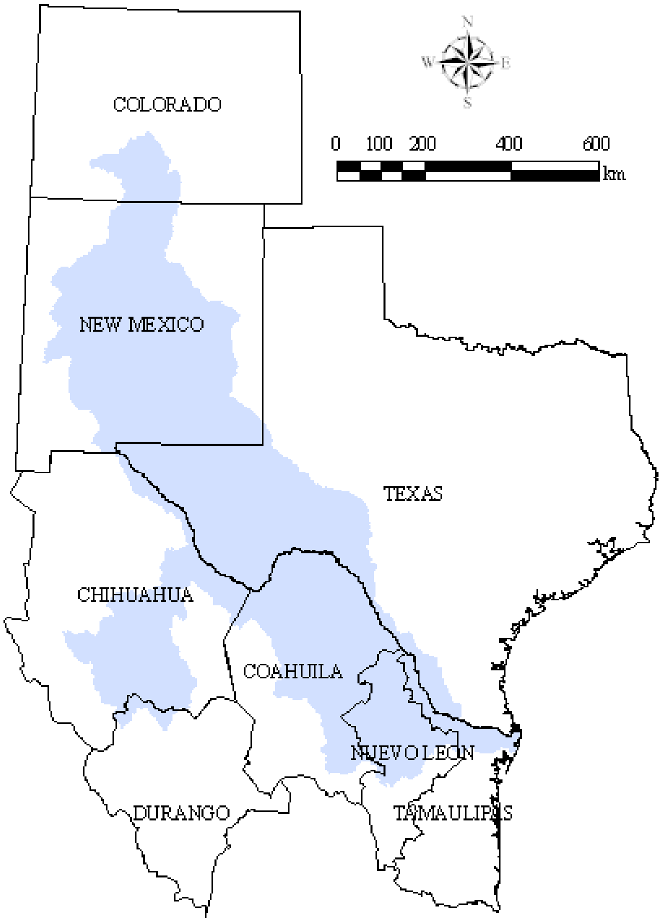

Figure 1-1 Location of the Rio Grande/Bravo Basin

The 1944 Treaty provides the framework for allocating the waters of the Rio Grande/Bravo below Ft. Quitman, Texas to the Gulf of Mexico (IBWC, 1944). This treaty authorized the construction of two international reservoirs, La Amistad and Falcon, which are managed jointly by the International Boundary and Water Commission (IBWC) and the Comisión Internacional de Limites y Aguas (CILA). These reservoirs and other projects were built for flood control and to increase irrigation capacity in the lower basin (IBWC, 1944).

The 1944 Treaty divides the water of the Rio Grande/Bravo from Fort Quitman to the Gulf of Mexico. Article IV of the 1944 Treaty allocates Mexico all of the waters of the San Juan and Alamo rivers and one-half of the flow in the main channel of the Rio Grande below Falcon Reservoir. Mexico is also allocated two-thirds of the flow in the main channel from the tributaries of the Rios Conchos, San Diego, San Rodrigo Escondido, and Salado, and Arroyo Las Vacas. These allocations to Mexico are on the conditions that the United States receive from these same six streams not less than 431million cubic meters (MCM) annually as an average in five-year cycles. Under Article IV, the U.S. receives one-half of all other flows not otherwise allotted, in the main channel of the Rio Grande/Bravo. The United States also receives all of the streamflow of the Pecos and Devils rivers, all the streamflow from Alamito, Terlingua, San Felipe, and Pinto creeks, all the discharge from Goodenough Spring, and one-half of the flow in the main channel of the Rio Grande below the Falcon Reservoir. Additionally, the U.S. is allocated one-third of the flow reaching the main channel of the Rio Grande from the Rios Conchos, San Diego, San Rodrigo, Escondido, Salado, and Arroyo Las Vacas, as long as this allocation is not less than 431 MCM annually as an average in five-year cycles. Lastly, the U.S. also receives one-half of all other flows not otherwise allotted, in the main stem of the Rio Grande (IBWC, 1944).

When these agreements were implemented, there was adequate flow to satisfy the treaty allocations to the respective countries. However, recent prolonged drought has brought to light the shortcomings of these set water agreements. The Rio Grande/Bravo is considered to be one of the most water stressed basins in the world. Rapid population growth and economic development, especially along the U.S.-Mexico border region, have placed additional strain on already limited water resources of the basin. In March 2007, the Rio Grande/Bravo was named one of the world's top ten endangered rivers by the World Wildlife Federation (WWF) (WWF, 2007). The WWF listed the Rio Grande/Bravo because over extraction of water has led to a multitude of physical problems for the river.

Smaller snow packs in the mountains and recent droughts coupled with over extraction have led to an extremely water stressed situation in the Rio Grande/Bravo basin (WWF, 2007). The basin exhibits symptoms of over extraction including low to no flow in sections of the river, proliferation of exotic species, and increased salinity. At times the river stops flowing in two sections of the basin. The first section of the river, known as the Forgotten River, is the reach of the river which extends along the Mexico-U.S. border, from El Paso/Ciudad Juarez to above the confluence with the Rio Conchos. The Forgotten River is remote, sparsely populated and little scientific information is known, compared to the rest of the Rio Grande/Bravo and often has little to no water flowing in this particular reach (Landis, 2001; Teasley and McKinney, 2005). The second section where flow has historically stopped is at the mouth of the river at the Gulf of Mexico.

Numerous times in the past, the Rio Grande/Bravo has stopped flowing into the Gulf of Mexico. Most recently in February 2001, the streamflow became so small that a sandbar developed at the mouth of the river. The formation of this sandbar prevents the river from draining into the Gulf of Mexico, effectively stopping the river (Texas Center for Policy Studies, 2002).

Other symptoms of a water crisis include increased salinity in the lower basin. Due to the increase in salinity, salt water species of fish have been found in the river as far inland as Falcon international reservoir, approximately 440 km (275 miles) upstream from the Gulf of Mexico. This increase in salinity has forced many native freshwater species out of this reach of the river (WWF, 2007).

Invasive species are also causing problems for the Rio Grande/Bravo. One example is Tamarisk (*Tamarix* spp.) or salt cedar, an exotic species introduced into the basin in the 1920's. This invasive species has found favorable conditions in the basin. Salt cedar is a highly drought and salinity resistant plant allowing it to thrive in the arid environments found along the Rio Grande/Bravo and allows it to overtake native riparian vegetation for habitat (DeLoach *et al*., 2000). Additionally, salt cedar consumes large quantities of water, contributes to the salinity in the river and chokes stream channels. Large stands of salt cedar have choked many sections of the Rio Grande/Bravo above

Amistad international reservoir and the lower Rio Conchos. The construction of large dams in the Rio Grande basin has changed the streamflows from conditions which favor native plant species to conditions that promote the growth and spread of salt cedar (Everitt, 1980).

Institutional problems have recently been highlighted in the basin. Due to prolonged and severe drought conditions in the late 1990's, Mexico was unable to satisfy treaty deliveries as specified by the 1944 Treaty. Mexico had a treaty-defined water debt to the U.S. and tensions increased between Texas and Mexican farmers (Texas Center for Policy Studies, 2002). This extreme drought led to the creation of IBWC Minutes 307 and 308 for joint data sharing, drought management and movement towards development of sustainable management in the Rio Grande/Bravo Basin (IBWC, 2002).

Due to the size and complexity of the Rio Grande/Bravo basin, conventional segment-specific approaches to water planning have become inadequate to meet the challenges of improving basin wide water management. To better satisfy sustainable water management objectives while meeting current needs in all sectors, in all segments, and in both nations, the Physical Assessment Project is developing a "whole basin" water resources planning model to analyze the physical opportunities for improved water management (NHI, 2006).

The Physical Assessment Project is a collaborative effort between technical and expert counterparts in Mexico and the United States aimed at exploring opportunities for improving management of the scarce water resources of the river through development and analysis of management scenarios. The Physical Assessment project is a “whole system” planning effort by 20 technical institutions, which are primarily non-governmental, from both sides of the border. The Project Steering Committee is comprised of The University of Texas at Austin, the Natural Heritage Institute, the University of Arizona, the Instituto Mexicano de Tecnología del Agua, the Universidad Autónoma de Ciudad Juárez, the Instituto Tecnológico de Estudios Superiores de Monterrey, the World Wildlife Fund-Mexico, and the U.S. Geological Survey.

The objective of the Physical Assessment Project is to examine scenarios for expanding the beneficial uses of the fixed water supply in the Rio Grande/Bravo basin to better satisfy an array of water management goals. These management goals include making agriculture more resilient to periodic conditions of drought, improving the reliability of supplies to cities and towns, and restoring lost environmental functions in the river system. The Physical Assessment Project is focused on creating management scenarios that fall within the current water allocation structure in the basin including treaties, compacts, and water rights. A hydrologic planning model is being used to evaluate the management scenarios for both physical feasibility and the ability to provide mutual benefits to stakeholders in the basin (NHI, 2006)

The Rio Grande/Bravo provides a good opportunity for the application of cooperative game theory. Water management scenarios are being developed through the input of basin stakeholders in both countries indicating their willingness to cooperate. Application of cooperative game theory to this transboundary basin can show the players what their increase in benefit may be under that cooperation and allows players to negotiate for a share of that increased benefit.

1.2 Objectives

This research is aimed at coupling cooperative game theory with a comprehensive water management model for a transboundary river basin. The objectives of this dissertation are to:

1. Construct and calibrate a water-planning model to represent the physical and institutional characteristics of a large scale, transboundary river basin (the Rio Grande basin) with multiple players, jurisdictions, and water uses in multiple sectors;
2. Utilize the water-planning model to calculate values needed in the cooperative game theory calculations (characteristic function values);
3. Create river basin games where players cooperate and learn the benefits of that cooperation. The games in this research give players the opportunity to negotiate and divide the benefits of their cooperation;
4. Create a cooperative game theory framework that can be used to evaluate the benefits of cooperation in other transboundary river basins and in future water management scenarios in the case study basin; and
5. Utilize the Rio Grande/Bravo Basin as a case study for the dissertation objectives.

1.3 Dissertation Outline

This dissertation is divided into six chapters. The Rio Grande/Bravo is used as a case study transboundary basin to meet the objectives set out in the first chapter. The second chapter provides an introduction to cooperative game theory concepts and a review of literature related to the application of cooperative game theory in water resources with focus on transboundary river basins. The methods for calculating the cooperative game theory values are outlined in the third chapter and the fourth chapter provides specific details of applying those methods to a selected water management game in the Rio Grande/Bravo basin. This chapter also describes in detail the water planning resources planning model developed for this application. The results of this application are contained in the fifth chapter and, finally, conclusions and recommendations are provided in the sixth chapter.

2 LITERATURE REVIEW

Cooperative game theory is applied to the Rio Grande/Bravo as a case study to determine the gains of cooperation, if they exist, for given water management scenarios. This section provides descriptions of concepts related to cooperative game theory and descriptions of applications of cooperative game theory to water resources problems with particular focus on specific applications to transboundary river basins.

2.1 Game Theory

First introduced formally by John von Neumann and Oskar Morgenstern in their 1944 text *Theory of Games and Economic Behavior*, game theory is the mathematical analysis of situations of conflict and cooperation. Game theory studies the way in which players strategically make decisions when the costs and benefits of each decision depend on the decisions of other players.

To ensure that game theory calculations are completed in similar units of cost and benefit, Utility Theory is often applied. Utility Theory assigns numerical values to outcomes to represent a player's preference (von Neumann and Morgenstern, 1944). Assigning utility to a player's outcomes ensures commensurate units for game theory calculations. Utility may either be ordinal or cardinal. Ordinal utilities simply order a player's outcomes by preference, the higher utility value the more preferred the outcome. Cardinal utilities assign values based on axiomatic preferences utilizing lotteries in which a player selects their preference in a series of random events. Cardinal utilities are used when the ratios of the differences between outcomes are important (Straffin, 1993). Utility is a useful concept because players in a game may value the same things differently. For example a poorer country may value a dollar differently than a rich country values that same dollar.

Games can be grouped into two major classes: non-cooperative and cooperative. In non-cooperative games, players only know their moves and strategically make decisions to maximize their benefits. Non-cooperative games may be zero-sum or non-zero-sum. In zero-sum games, the benefit to one player is a loss to another. The classic example of a non-cooperative game is the prisoner's dilemma game, which was originally designed by Flood and Drescher in 1950 (Straffin, 2004). Albert Tucker later formalized the game and put it in the context of prison sentence payoffs and named the game the "Prisoner's Dilemma" game (Straffin, 1993). In the Prisoner's Dilemma game there are two suspects held in separate rooms and each has to decide whether to confess or not confess to their crime. Both prisoners must make a decision based on what they believe the other prisoner will do, because if one decides to confess while the other does not, the one who confesses gets a light sentence while the other gets a heavy sentence if he does not confess. However if they both confess they both receive a light sentence and if they both do not confess they receive no sentence. Each prisoner must make strategic decisions to receive the minimum sentence based on what they believe the other prisoners decision will be.

In cooperative games, all possible strategy sequences that could occur are determined and the consequences are made available to the players prior to play. Players in a cooperative game have communication prior to the game and make binding agreements, known as coalitions. Cooperative games allocate the costs and benefits of coalition decisions to the individual players in that coalition.

2.1.1 COOPERATIVE GAME THEORY CONCEPTS

This section provides a general overview of the concepts employed in cooperative game theory. Further details and necessary equations for performing cooperative game theory calculations are provided in the Chapter 3.

Generally, cooperative games are multi-player games where any number (n) of players, $n > 1$, may be involved in the game. Players in a game represent stakeholders or decision makers in a resource allocation problem. In the case of water resources, players may include, but are not limited to, countries, states, or individual water users such as municipalities, irrigators, or industries. In cooperative game theory, communication takes place between the players prior to the game and players are allowed to make joint and binding agreements called "coalitions." In any n-player game there are 2^n-1 possible coalitions which may form. The coalitions range from non-cooperative coalitions to full cooperative coalitions (the grand coalition) and subsets of players (partial coalitions) that may also form coalitions.

Typically, cooperative games are expressed in "characteristic form," meaning that the outcomes of all possible strategies are expressed in terms of a characteristic function. Denoted as v, the characteristic function is used to represent the benefits of cooperation to each coalition. Characteristic function values for a water resources cooperative game are often calculated using a water resources model, as will be discussed in Section 2.3.1.

Given the characteristic function of a cooperative game, various allocation methods can be utilized to distribute the total benefits of each coalition to its players. Benefits from cooperation in water resources management can be physical gains, such as hydroelectricity generation, or increased water quality or availability, or they may be economic gains, such as increased agricultural profit. Players in a cooperative game are assumed to behave rationally and allocations are made with the constraint or assumption that no player in a coalition will accept an allocation that is less than they can gain by themselves without cooperation. A commonly used method for determining the range of the possible allocations that players might agree to is the "Core." The Core is a set of allocations (solutions) that are not dominated by any other allocations; in other words, these are allocations that all players in a coalition are willing to accept (Gillies, 1953). In game theory terms, these allocations are known as "imputations" and they satisfy three necessary conditions: 1) efficiency, which requires all of the value obtained by the coalition be distributed to its players; 2) individual rationality, where no player will accept an allocation that is less than they could gain by themselves without cooperation;

and 3) Pareto optimality, which ensures that the individual allocations sum to the value of the coalition (Gillies, 1953).

The Core provides bounds on the minimum and maximum benefit that each player is likely to gain from cooperation (Gilles, 1953). The bounds for the Core are derived from the characteristic function values for each coalition. The larger the Core is, the larger the negotiating space is. If the Core does not exist, there are methods for expanding the Core to search for other solutions. If the Core exists, various allocation methods can be employed, such as the Shapley value, to determine effective allocations among the players.

If the Core exists, the Shapley (Shapley, 1953) and the Nucleolus (Schmeidler, 1969) allocations can be used to fairly and equitably distribute the gains of a coalition to its players. In general terms, the Shapley allocation is the average marginal contribution of each player to a coalition, or each player's benefit added through cooperation in a coalition. The Nucleolus is the lexicographic minimum of excesses in the allocations where an excess is defined as the difference between the minimum allocation and the assigned allocation. The Nucleolus minimizes these excesses to all players.

Stability indices are a useful tool for ensuring that players are satisfied with allocations from a coalition. Once allocations of coalition gains have been determined for each player in a coalition, stability indices may be calculated to determine the extent to which allocations from the Core satisfy the coalition members. The Gately Propensity to Disrupt (Gately, 1974) is a useful method for calculating the stability of a solution.

2.1.2 GAME THEORY IN WATER RESOURCES

Cooperative game theory has been successfully applied in numerous areas of resource management such as fisheries, forest management and pollution control. Zara *et al.* (2006) provide a thorough review of cooperative game theory applications to natural and environmental resources problems other than water resources. This review will focus on cooperative game theory applications with respect to water resources management. Cooperative game theory applications in water resources management can be categorized as either classical or non-classical. Classical games require users to specify all possible sequences of strategies prior to play, while non-classical games allow strategies to develop through repeated play (Sage and Rouse, 1999). This section provides an overview of both classical and non-classical cooperative game theory applications to water resources management.

2.1.2.1 Non-Classical Game Theory in Water Resources

There is a developing field of non-classical game theory with applications to conflict analysis in water resources management. These non-classical games include metagame analysis (Hipel *et al.*, 1976; Howard, 1971), hypergames (Okada *et al.*, 1985) and graph models (Nandalal and Hipel, 2007; Hipel *et al.*, 1997; Fang *et al.*, 1997). These games allow strategies to evolve over time through repeated play, and the players typically do not have communication prior to play. The relative preferences of each player must be specified prior to the game. Through repeated play, a player's responses to other players' decisions are tested and strategies for resource allocation that minimize conflict are created over time (Nandalal and Hipel, 2007).

While metagames and graph models have proven to be useful tools for conflict analysis in water resources applications, they require repeated play to allow strategies to evolve over time. Rather than using a method to minimize conflict, the intent of this research is to create games where players cooperate and learn the benefits of that cooperation. The games in this research give players the opportunity to negotiate and divide the benefits of their cooperation. Since the methods described in this section do not rely on cooperation through coalition building they will not be considered further here.

2.1.2.2 Cooperative Game Theory in Water Resources

Cooperative game theory has been utilized for decision making in multiple areas of water resources management. Rogers (1969) presented one of the first applications of game theory to water resources management found in the literature. The author demonstrated that game theory can provide a basis for analyzing treaty negotiation between India and the province of East Pakistan (now Bangladesh) for their shared water resources of the Ganges and Brahmaputra rivers. Since that application, cooperative game theory has been applied to various water management topics such as cost allocation for water development projects, water quality, aquifer management and transboundary water resources management. This section contains brief descriptions of game theory applications to water resources. Section 2.3 deals specifically with transboundary water resources management.

Cooperative game theory has been demonstrated to be a useful tool for fairly allocating the cost of shared water resources projects to the water consumers. Suzuki and Nakayama (1976) illustrated the allocation of costs and benefits of a water development project (i.e. dam construction) to both agricultural and municipal users. This idea of allocating costs and benefits to multiple users was echoed by Straffin and Heaney (1981) where costs were equitably allocated between different Tennessee Valley Authority projects (hydropower, flood management and navigation).

A common application of cooperative game theory has been cost sharing for regional wastewater treatment. Many authors have compared the costs and benefits of individual users treating their wastewater as opposed to using a regional treatment facility (Giglio and Wrightington, 1972; Heaney and Dickinson, 1982; Loehman *et al*., 1979). Along the same lines as regional wastewater treatment, Young *et al*. (1982) used cooperative game theory to show that a regional water supply was more beneficial to the stakeholders for a case study in Sweden. Adding onto the idea of cost sharing for regional water projects, Dinar *et al*. (1986) and Dinar and Yaron (1986) included reuse of municipal water for irrigation to the analysis of regional wastewater treatment. This extended the cooperative game to multi-user games with municipal and agricultural users.

Cost sharing games have also been applied in the area of water quality. Dinar and Howitt (1997) utilized cost allocation games to minimize pollution, allocating the costs of regional treatment of irrigation drainage. Rather than allocating the costs and benefits of treatment, Kilgour *et al*. (1988) allocated allowable pollutant discharge. The water quality standard and the total allowable concentration of chemical oxygen demand (COD) discharge were determined. The allowable COD discharge was allocated among the dischargers, demonstrating how loadings can be reduced efficiently by sharing the effort with all dischargers.

Cooperative game theory has been applied to a variety of water resources allocation projects. As discussed above, the literature shows that cooperative game theory is a useful tool for allocating the costs and benefits of regional projects but little work has been done in the area of transboundary river basins. The next section outlines the relevant literature for cooperative game theory in transboundary river basins.

2.2 Cooperative Game Theory in Transboundary River Basins

The previous section discussed how cooperative game theory has been utilized to analyze various water resources problems. However, limited work has been done on applying cooperative game theory to transboundary water sources and river basins. Cooperative game theory has been utilized to allocate quantities of water from a shared water source. In a sequence of papers, Becker and Easter (1997 and 1999) applied cooperative game theory to water allocation from the Great Lakes. The authors demonstrated that a cooperative solution for equitable water sharing could be calculated for the transboundary lakes. An interesting point highlighted by the authors is that once partial coalitions were formed and fair allocations were made, the non-cooperative coalitions could be induced to cooperate. The Grand Coalition was shown to be the best solution for all players. Although these applications deal with a transboundary water sources, this section focuses specifically on transboundary river basins.

Cooperative game theory has been successfully applied to the Ganges and Brahmaputra basin (Rogers, 1969; Rogers, 1993), the Nile basin (Wu, 2000; Wu and Whittington, 2006), and the Euphrates and Tigris (Kucukmehmetoglu, 2002; Kucukmehmetoglu and Guldmann, 2004) rivers. In addition, game theory has been applied for water trading from the Nile among the Middle East countries of Egypt and Israel, and with the regions of the Gaza Strip and the West bank (Dinar and Wolf, 1994). This section outlines the water planning models, the coalitions considered, and the political structures included in these transboundary river basin cooperative games.

2.2.1 WATER PLANNING MODELS

All of the transboundary river basin cooperative games discussed in this section used optimization models to calculate the characteristic functions of their games. Nonlinear Programming was applied in the Nile game (Wu, 2000; Wu and Whittington, 2006), which maximized the net economic benefit to each player and considered physical basin constraints. The Ganges-Brahmaputra (Rogers, 1969; Rogers, 1993), Euphrates-Tigris games (Kucukmehmetoglu, 2002; Kucukmehmetoglu and Guldmann, 2004;

Kucukmehmetoglu, 2009), and the Mid-East water trading game (Dinar and Wolf, 1994) utilized Linear Programming. In the case of the Ganges-Brahmatputra and Euphrates-Tigris games, the objective was to maximize the net benefit to each player in terms of monetary value constrained by the physical system. The monetary value in these models was derived from hydropower production and irrigation uses. Rogers (1969), Wu (2000), and Kucukmehmetoglu (2002) concluded that their water resources models were proof-of-concept models, rather than detailed and accurate simulations, due to lack of data for the respective basins. Their models did not accurately represent their river basins and better data is required to improve their games.

Dinar and Wolf (1994) utilized a simple linear optimization model that maximized water deliveries to players in a water market subject to price and water quantity constraints. This model used a simplified Nile basin representation focusing on the economics of the game rather than the physical characteristics of the system. Including more detailed modeling into their game would improve the reliability of their water availability in their water trading calculations.

2.2.2 COALITIONS

Typically, when cooperative game theory has been applied to a transboundary river basin, the players have been the basin riparian countries. There does not seem to be an example in the literature where the players in a transboundary river game are individual users within the countries. Rogers (1969) considered a two-player game between India and Pakistan. In his second application (1993), a new game was considered and expanded to include the three players of India, Bangladesh, and Nepal. Inclusion of the third player added to the richness of the problem and more accurately represented the basin. In the case of the Nile game, four players were considered (Egypt, Sudan, Ethiopia and, represented as a single player, the equatorial states of Uganda, Kenya, Tanzania, Burundi, Rwanda and Democratic Republic of Congo. As players are added, the number of imputations (2^n-1 for *n* players) and the complexity of the problem increases significantly, but the richness of the solution also increases.

2.2.3 POLITICS

Politics have rarely been considered in cooperative transboundary games. The only game that includes politics is the Mid-East water trading game (Dinar and Wolf, 1994). Dinar and Wolf (1994) utilized a method called the Political Accounting System (PAS), which takes account of how the players would behave under their respective countries' political constraints. These political constraints include existing treaties, agreements, and political behavior. The PAS is a methodology to create utility for games based on each player's political attitudes. Based on the player's political attitudes, the PAS calculates the likelihood of coalition formation. This research will not utilize PAS for incorporating political behavior, but bi-national policies are included in the Physical Assessment model. The bi-national agreements of 1906 and 1944 are included as constraints and all required treaty deliveries are accounted in the model.

2.3 Summary

A review of the literature shows that cooperative game theory has been used successfully to estimate the potential benefits of cooperation among riparian countries in transboundary river basins. Cooperative game theory also provides tools to fairly and equitably allocate the gains of cooperation to the players. The literature shows that the transboundary river games have been somewhat limited, i.e., games among countries, rather than individual users. This research aims to demonstrate cooperative game theory applied to individual users in a transboundary system as players rather than just the riparian countries. Creating a game in this manner distributes the benefits in a more detailed manner to individual users rather than to the countries.

The literature has shown that the water planning models utilized in transboundary cooperative games tend to be oversimplified or lack accurate data. Additionally there has been little inclusion of policies into transboundary cooperative games. This research develops a comprehensive and reasonably accurate model that follows the constraints of existing water uses, management and international treaties. A detailed water planning model coupled with cooperative game theory concepts provides stakeholders in the Rio Grande/Bravo basin with a powerful tool for quantifying the benefits of cooperating to improve water management in the entire basin.

3 METHODOLOGY

This section outlines the methods used to meet the objectives of this research. Cooperative games are developed based on stakeholder defined water management scenarios. Players in the games are selected based on the water management scenarios and the characteristic function values for those players are calculated. To calculate the characteristic function values, a water management model is developed to simulate the physical outcomes of the water management scenarios. The outcome of a game is a quantification of the benefits of player cooperation and the opportunity for players to negotiate and divide the benefits of their cooperation.

An *n*-person cooperative game is applied to the Rio Grande/Bravo basin case study area. The games are developed from the Physical Assessment Project scenarios that have been shown to have physical feasibility after screening with the water resources planning model. This application will be discussed in detail in Section 4. In general, the steps for the cooperative game analysis in a transboundary river basin include:

1. Determine the players in the game
2. Determine coalitions which may form for a selected scenario
3. Calculate the characteristic functions for each coalition using the results from the water management model
4. Determine the existence of the Core
5. Apply a method to allocate the gains of the coalition to the individual players

6. Calculate the stability of the solution

The Appendix contains an example of an application of cooperative game theory to a four player cooperative game in the transboundary Syr Darya basin in Central Asia.

3.1 Players and Coalitions

Players in the Rio Grande/Bravo cooperative game may represent, but are not limited to; countries (2), states (5 Mexican and 2 U.S.), irrigation districts, or smaller stakeholders such as irrigators, reservoir operators or municipalities. Different sets of players are selected for various water management scenarios. Once the *n* players are chosen, then 2^n-1 possible coalitions can be formed. Coalitions will range from an individual player acting alone (non-cooperative or status quo), to a coalition of all players (full cooperation or the Grand Coalition). Partial coalitions among subsets of players may also be considered.

After selecting the players and determining the coalitions for a particular scenario, the characteristic function is calculated for each coalition using a water resources planning model. The simulation model for the Rio Grande/Bravo case study is described in detail in Section 4. The planning model is run for each coalition ranging from non-cooperative to full cooperation and the resulting benefits are assigned to the players. Benefits can be based on water volumes or economic values, e.g., current water market information. From these benefits and the results of the model, the characteristic functions for each coalition are calculated and used to determine the Core.

3.2 The Core

The Core is a set of non-dominated allocations of gains from cooperation to the players. The individual allocations are known as imputations (Schmeidler 1969) denoted as Ω_j for player j. In other words; the Core is a set of feasible allocations that all players would be willing to accept and are larger than the allocation they would get if they didn't cooperate. Imputations from the Core satisfy individual and collective rationality (Pareto Optimality) (von Neumann and Morgenstern, 1944).

Individual rationality, the concept that no player will accept an allocation smaller than what they can receive without cooperation, can be expressed as:

$$\Omega_j \geq v(j) \qquad \forall j \in N$$ **Equation 3-1**

where:

Ω_j = an allocation to player j from the Core

$v(j)$ = the non-cooperative characteristic function value of player j

N = the set of players in the game

Collective rationality states that the gains obtained from forming the Grand Coalition will be divided among the players:

$$\sum_{j \in N} \Omega_j = v(N)$$ **Equation 3-2**

where:

$v(N)$ = the characteristic function of the Grand Coalition

3.3 Allocation Methods

Once the values of cooperating in various coalitions are known, the players must agree on a division of any gains over and above what can be gained through independent (non-cooperative) action. Several allocation schemes have been proposed in the literature and are discussed here.

Shapley (1953) proposed distributing the gains of a coalition to individual players based on their marginal contribution of benefits to the coalition. The Shapley value for player j in a coalition is based on the player entering into an already forming Grand Coalition. Player j's marginal contribution or benefits received, for coalition formation is calculated based on this entry into the coalition as:

$$\varphi_j = \frac{1}{n!}\sum_{j \in S}\left((s-1)!(n-s)!\left[v(S) - v(S-j)\right]\right) \qquad \textbf{Equation 3-3}$$

where:

φ_j = Shapley value for player j

n = total number of players in the game

s = number of players in coalition S

S = coalition S which contains j

$v(S)$ = characteristic function for coalition S

$v(S-j)$ = characteristic function for coalition S without player j

This equation considers all coalitions that may form containing player j. All orderings of the players in the Grand Coalition have the same probability of occurring, namely, $\frac{(s-1)!(n-s)!}{n!}$. For calculations, as player j coalition S, created by the players which joined before, that player is awarded the marginal contribution (or additional benefit) of $[v(S)-v(S-j)]$.

An alternative to the Shapley allocation is the Nucleolus, a single point allocation solution that always exists in a non-empty core (Schmeidler, 1969). A Shapley allocation may not always occur in the Core, but the Nucleolus is guaranteed to occur in the Core. The Nucleolus is calculated by finding a vector of imputations $\Omega = (\Omega_1, \Omega_2, \ldots, \Omega_n)$ that minimizes the maximum of excesses, $e(\Omega, S)$, over all coalitions S subject to $\sum \Omega_j = v(N)$, where Ω_j is an allocation to player j, and all allocations, Ω_j, must sum to the characteristic value of the Grand Coalition. The Nucleolus can be calculated as a linear programming problem (Straffin, 1993).

The Shapley allocation is calculated from a player's contribution to a coalition, while the Nucleolus aims to minimize dissatisfaction (excesses) of players by increasing their allocations. Wu (2000) and Wu and Wittington (2006) noted that the Nucleolus is always contained in the Core (if one exists) and ensures that the allocation satisfies collective and individual rationality. Additionally, the Nucleolus in effect 'levels the playing field' meaning that it is not based on a player's contribution to a coalition and gives them the opportunity to minimize their dissatisfaction (*i.e.* increase their allocation).

3.4 Coalition Stability

The likelihood that a player will leave the Grand Coalition because they are dissatisfied with their allocation, say from the Shapley or Nucleolus method, can be quantified through "stability indices." One method to measure this dissatisfaction with an allocation is the Gately "propensity to disrupt" which is described in this section.

The "propensity to disrupt" (d_j) of player j is calculated as (Gately, 1974):

$$d_j = \frac{\sum_{i \neq j} \Omega_i - v(\{N-j\})}{\Omega_j - v(\{j\})}$$

Equation 3-4

where:

Ω_j = allocation to player j

$\sum_{i \neq j} \Omega_i$ = the sum of the allocation to all players $i \neq j$

$v(j)$ = characteristic function for a non-cooperative player j

$v(N\text{-}j)$ = characteristic function of the Grand Coalition without player j

The propensity to disrupt is measured for a player j relative to the other players in a coalition. The propensity to disrupt is the ratio of what the players in coalition $\{N - j\}$ stand to lose if player j leaves the Grand Coalition $\{N\}$, to what the player j would lose by leaving the Grand Coalition. If d_j is positive and larger than a specified value, player j will tend to disrupt the Grand Coalition unless their allocation is increased. This value is set by the game's players. For example, if a player's propensity to disrupt were 100, then if the player left the grand coalition they would cause a loss 100 times greater to the remaining coalition members than to themselves. However, if their propensity to disrupt is 1, then they cause the same loss to themselves as to the remaining coalition members. The propensity to disrupt is used to eliminate imputations in the Core for which a player's propensity to disrupt is higher than a specified value.

4 APPLICATION

This dissertation has described in general terms the methods which may be utilized in the application of cooperative game theory to transboundary river basins. This section describes the specific application of the cooperative game theory methods to the Rio Grande/Bravo case study. Included in this section is the description of the comprehensive water planning model and its validation process as well as the development of a water management scenario into a cooperative game framework. Results from this application are described in Chapter 5. In addition to the Rio Grande/Bravo application, an application of a 4 player cooperative game in the Syr Darya in Central Asia is described in the Appendix.

4.1 Water Resources Planning Model

A water resource planning model was created for the Rio Grande/Bravo basin using river basin simulation software. An optimization model was not chosen as the planning model for the Rio Grande/Bravo cooperative game because formulation of a single objective function for this large basin would prove difficult and may be unrealistic. The water resources planning model for the Rio Grande/Bravo basin has been constructed in the Water Evaluation and Planning (WEAP) system (www.weap21.org, Danner *et al.*, 2006). WEAP is a flexible river basin simulation software which utilizes a user-friendly graphical interface to construct the model schematically, enter data, allocate water to users, and view results. WEAP is a demand driven allocation model operating on basic principles of water balance accounting, linking water supplies from rivers, reservoirs, and aquifers with prioritized water demands in an integrated system.

The Rio Grande/Bravo WEAP model includes the main stem of the river from Elephant Butte Reservoir in New Mexico to the Gulf of Mexico. A hydrologic break occurs in the main stem of the Rio Grande/Bravo in a reach commonly known as the "Forgotten River." This reach, located just below Fort Quitman, Texas to above the confluence with the Rio Conchos, often has little or no streamflow (Teasley and McKinney, 2005). Due to this hydrologic break, water management decisions made upstream from Elephant Butte to El Paso/Ciudad Juarez have little effect on the river from the confluence with the Rio Conchos to the Gulf of Mexico.

Numerous tributaries in the Rio Grande/Bravo basin are included in the WEAP model. The main tributaries in the U.S. include the Pecos and Devils rivers, Goodenough Spring, and Alamito, Terlingua, San Felipe and Pinto Creeks. The main tributaries on the Mexican side include the Rio Conchos and its tributaries, Rios San Diego, San Rodrigo, Escondido, Salado, San Juan, Alamo and Las Vacas (Danner *et al.*, 2006).

4.1.1 HYDROLOGIC DATA

The information to support the Rio Grande/Bravo model was derived from numerous sources. Most of the data were obtained from a relational Arc Hydro geodatabase created for the Rio Grande/Bravo basin (Patiño-Gomez and McKinney, 2005). The Rio Grande/Bravo geodatabase contains geographic, hydrologic, hydraulic, water demand and related data for the entire basin. The geodatabase was created through the cooperation of the Center for Research in Water Resources (CRWR) at The University of Texas at Austin, the Texas Commission on Environmental Quality (TCEQ), the Mexican Institute of Water Technology (IMTA), and the National Water Commission (CNA) of Mexico (Patiño-Gomez *et al*., 2007).

In addition to the data from the geodatabase, the Rio Grande/Bravo model utilizes naturalized flow and channel loss data from the TCEQ Water Availability Modeling (WAM) project (TCEQ, 2005). Naturalized flows are calculated to represent the natural streamflow in a river in the absence of human development and water use. A series of monthly naturalized flows were calculated for a sixty year period (1940-2000) for the Rio Grande/Bravo basin from El Paso to the Gulf of Mexico and all the major tributaries including the Pecos River and the Rio Conchos (Brandes, 2003). As part of these calculations, channel losses were determined, including channel seepage, evaporation, and evapotranspiration.

In the Rio Grande/Bravo model, naturalized flows are used as input for headflows for 21 rivers and creeks and incremental flows for 22 sites in the basin to represent unaccounted gains along stream reaches (Danner *et al*., 2006). In addition to surface water, groundwater is included in the model as a source of water supply for both countries. Data related to groundwater storage capacity, initial storage, maximum withdrawal, and natural recharge are included in the model.

4.1.2 WATER DEMANDS

There are 178 water demands (demand sites) included in the Rio Grande/Bravo model, including municipalities, irrigation, mining, industrial, and other uses. Due to the large number of individual water users in the basin (over 1,600 in Texas alone) many of the demands were aggregated into larger demand sites in the model. Demands for these water users were combined based on type of demand, location in the basin, and legal jurisdiction. Table 4-1 is a summary of the number and type of surface water demand sites for each country. In addition to surface water demands shown in Table 4-1, there are 22 Mexican demand sites with a total water demand of 1,655 million cubic meters (MCM) satisfied by groundwater deliveries and 21 U.S. demand sites which can draw a maximum of 2,840 MCM of groundwater.

Table 4-1 Surface Water Demand Type, Number, and Demand Volume (MCM) for Demand Nodes by Country in the Rio Grande/Bravo WEAP Model

Demand Type	Mexico		United States	
	Number of Demand Nodes	Annual Demand (MCM)	Number of Demand Nodes	Annual Demand (MCM)
Municipal	15	564	23	283
Irrigation	27	3,798	55	2,153
Other	0	0	15	11
Total	**42**	**4,362**	**93**	**2,447**

In the monthly time-step model, allocation of water to demands each month is based on user-defined priorities. First, the model delivers water to all priority one users and then any remaining water in the system is allocated to priority two users, and so on. This type of priority allocation allows the model to mimic the actual water allocation policies in the basin. For example, in both Texas and Mexico, municipal demands always have priority over any other use in the basin. When water is scarce in the basin, priority allocation ensures that water is delivered to municipal demands before any other use, such as irrigation or industry.

4.1.3 RESERVOIR CAPACITY

The model contains 25 reservoirs (Figure 4-1) with a total storage capacity of 22,034 MCM. Two international reservoirs in the basin, Falcon and La Amistad, are owned and operated jointly by the U.S. and Mexico and have a combined capacity of 7,177 MCM. Fourteen reservoirs in the basin are owned by Mexico with a total storage capacity of 11,424 MCM. Five reservoirs in the model are owned by the U.S. and have a total storage of 3,433 MCM. In the model, each reservoir has a number of storage zones and each zone has a specific set of operating rules.

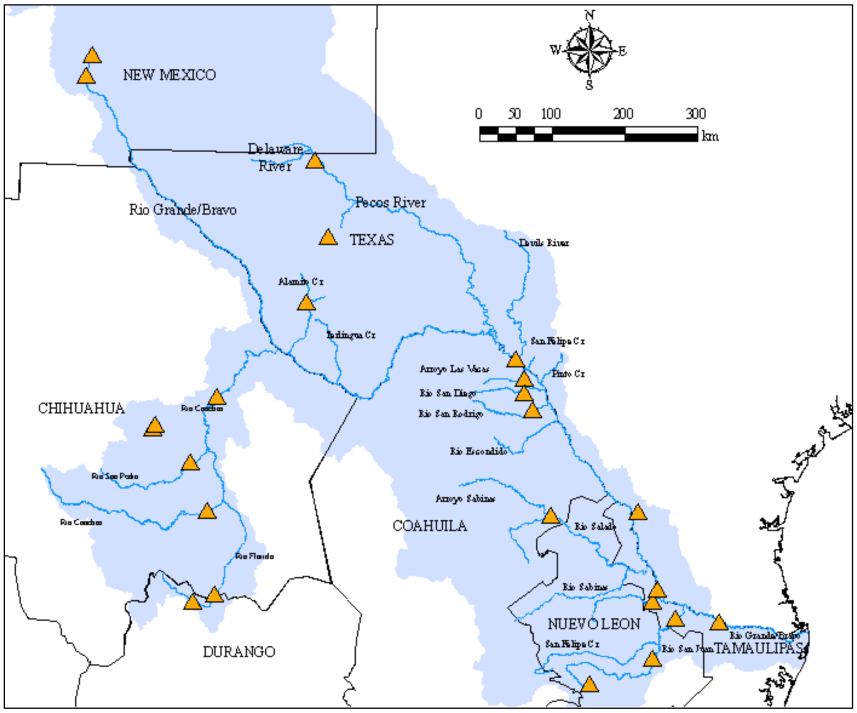

Figure 4-1 Locations of the Reservoirs included in the Rio Grande/Bravo Water Planning Model.

4.1.4 LEGAL INSTITUTIONS REPRESENTED IN THE WATER PLANNING MODEL

WEAP has a scripting language that allows the user to create rules for a basin such as operation rules for reservoirs or allocation rules for treaties. The Rio Grande/Bravo model uses this scripting capability to represent the legal framework of water allocation in the basin. The model includes relevant policies from the 1906 Convention (IBWC, 1906) and the 1944 Treaty between the U.S. and Mexico (IBWC, 1944), the Interstate Compacts for the Rio Grande (Colorado, New Mexico and Texas) (USBR, 1939), and the Texas Watermaster rules for Texas water rights (TCEQ, 2008).

An example of using scripts in WEAP is the tracking of water allocations under the 1944 Treaty between the U.S. and Mexico. Section 2.1.1 of the 1944 Treaty outlines the apportionment of Rio Grande/Bravo flows below Fort Quitman, Texas. The model has scripts which track the volume of water delivered to the U.S. from the Mexican tributaries averaged over a five-year period. Scripts are also used to track the ownership of the water stored in the international reservoirs, Amistad and Falcon (Danner *et al.*, 2006). The volumes for each country are tracked as accounts and releases to downstream demands are deducted from the appropriate account. These accounts are used to limit downstream demands based on the amount of water available in storage for each country.

4.1.5 MODEL TESTING

Model testing was completed in two stages. The first stage was calibration, where parameters in the model were adjusted so that the model results were closer to the historical conditions in the basin. The second stage in the testing process was model validation, where historic conditions were entered into the model to determine if the model was capturing historical operations within the basins. Both stages of model testing are described in this section.

4.1.5.1 Model Calibration

To calibrate the Rio Grande/Bravo model, reservoir conservation storage in all 25 reservoirs in the model and stream channel conveyance losses were adjusted to try to achieve agreement between model and historic values for several variables. These parameters were chosen for the calibration process because additional information was available for them. Other parameters in the model could be adjusted for better calibration, but without additional information it is difficult to know if the adjustments are reasonable or grounded in reality.

The first parameter adjusted in the calibration process was reservoir conservation storage. Examination of historical storage levels in Mexican reservoirs revealed that water was often stored in the region above the declared ('official') conservation storage zone. To compensate for this and to capture the historical reservoir behavior, the conservation zones in those reservoirs were adjusted and the resulting storage levels were compared to the historical levels.

Next, stream channel conveyance losses were adjusted. Documentation exists which define two different sets of losses for the several of the same stream reaches in the basin; one set from the TCEQ WAM model (Brandes, 2003) and a second set from the Mexican National Water Commission, *Comision Nacional del Agua* (CONAGUA) (Collado 2002; Aldama 2008). Calibration of the model with the two sets of parameters and combinations of them revealed that using a combination of parameters provides the best representation of historical conditions in the basin. For the rivers and streams in the

U.S., the TCEQ conveyance losses provide the best results compared to the historical values, while the CONAGUA losses provide better results for the Mexican streams and rivers. For the main stem of the Rio Grande/Bravo, the TCEQ conveyance losses were used. Details of this process are found in Sandoval-Solis *et al*. (2008).

4.1.5.2 Model Validation

Model validation was performed by entering known historic water demands into the model, running the model for a 15-year period extending from 1978 to 1992, and comparing results. This period was used because most of the water demands are known for this period and all of the reservoirs in the system were constructed and operational during that time period. The modeled storage values in the U.S. and Mexican accounts in both international reservoirs were compared to the historical storage values (see Figures 4-2 and 4-3). International reservoir storage was chosen as a performance measure for the model because these reservoirs are located in the lower part of the basin and are highly affected by operations in the upper part of the basin, as well as, demands in the lower part of the basin.

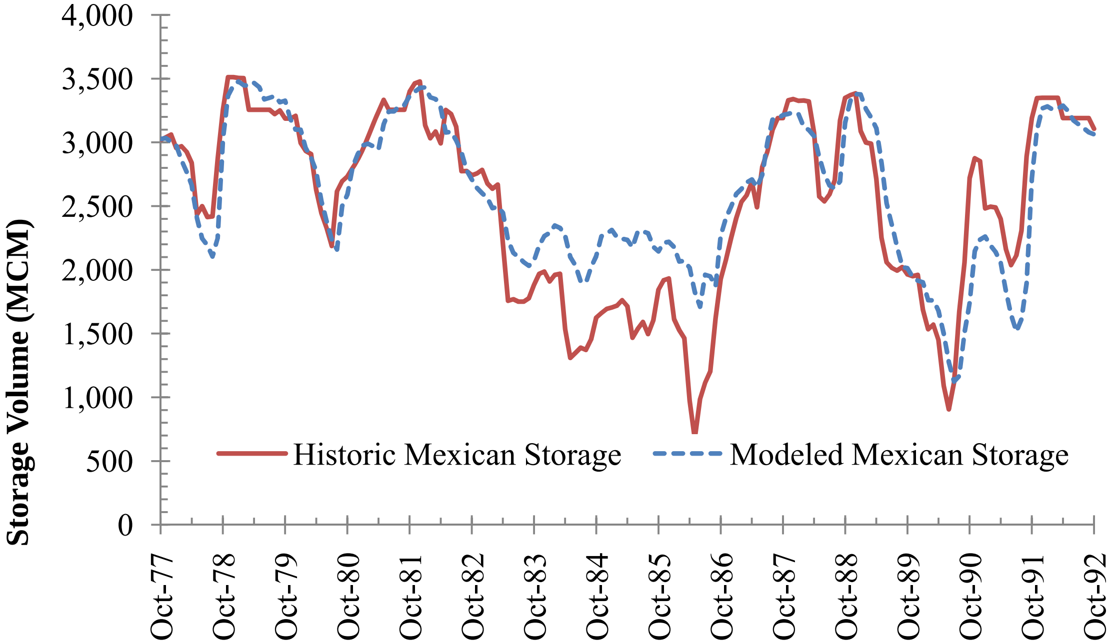

Figure 4-2 Historic vs. Modeled Reservoir Storage for the Mexican Accounts in the International Reservoirs

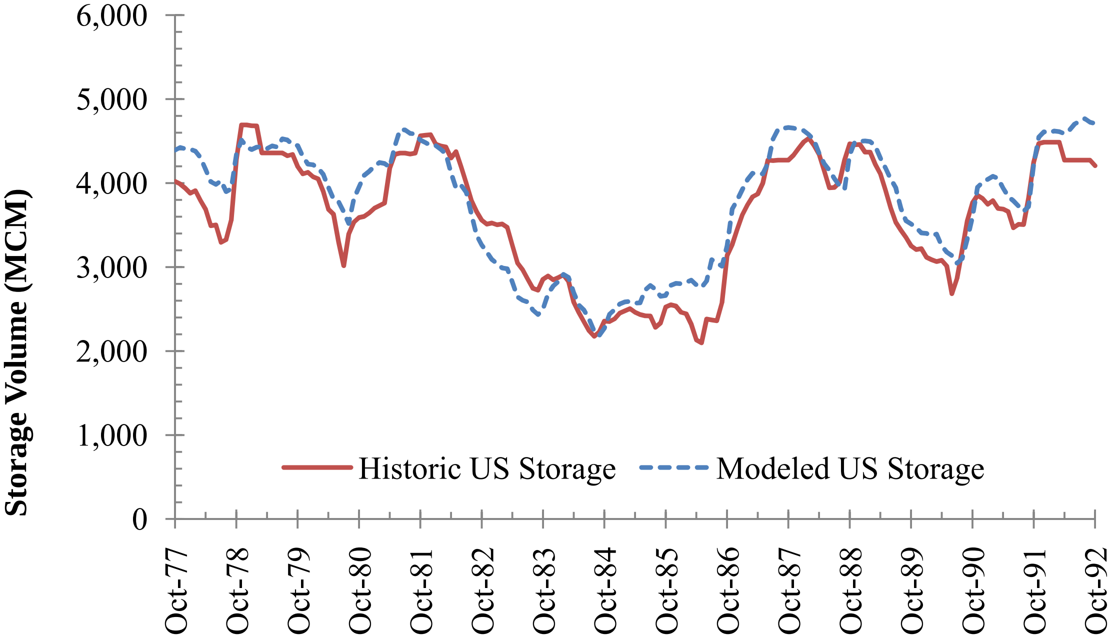

Figure 4-3 Historic vs. Modeled Reservoir Storage for the U.S. Accounts in the International Reservoirs

By inspection of the graphs, the modeled storage values follow the same trends as the historic values for both the Mexican (Figure 4-2) and the U.S. (Figure 4-3) accounts. The difference between the historic and modeled values for the 15-year period is 3.6% for the Mexican accounts and 4.3% for the U.S. accounts. The modeled storage values tend to be slightly higher than the historic storage values. The validation results demonstrate that the Rio Grande/Bravo model provides a reasonable representation of the water management in the basin.

4.2 Water Demand Reduction Game

The Water Demand Reduction game utilizes a scenario based on a water rights buy-back program implemented in the Rio Conchos basin in Mexico. In 2003, Mexico began a program to purchase (buy-back) existing water rights from Rio Conchos irrigation districts. This program, named PADUA (Programa de Adecuación de Derechos de Uso del Agua y Redimensionamiento de Distritos de Riego) was developed to reduce water allocations with the intention to buy back water rights that were unlikely to be met in drought periods (SAGARPA-FAO, 2005). The program purchased groundwater and surface water rights from the Delicias Irrigation District (DR005) and surface water rights from the Bajo Conchos Irrigation District (DR090). The Water Demand Reduction game examines water rights buybacks only in District 005 and is based on an increase in the water buy-back volumes above those originally proposed by the PADUA program.

Under the PADUA program, the water concessions to District 005 were reduced from 1,130.6 million cubic meters per year (MCM/year) by buying-back surface and groundwater rights. In the Water Demand Reduction game, District 005 agrees to sell surface and groundwater rights to reduce their water demand from 1,130.6 MCM/year to a lower volume of 628.1 MCM/year (Table 4-2) (SAGARPA-FAO, 2005). PADUA proposed to split the buy back with 83% being surface water rights and 17% being groundwater rights. The Water Demand Reduction game uses these same percentages of surface water and groundwater buybacks (Table 4-2). Although buying back surface water rights would leave more surface water available to downstream users, groundwater is an important resource for District 005. The Meoqui aquifer is naturally recharged through infiltration from the surface agricultural water application. Reducing the demand for groundwater from the Meoqui aquifer helps to protect against over-pumping of groundwater. Details of the modeling for this scenario can be found in Sandoval-Solis *et al*. (2008), but the volumes of the buy-backs have been increased and correspond to the values shown in Table 4-2.

Table 4-2 Water Rights Reduction in District 005 in the Rio Conchos for the Water Reduction Game

	Water Demand		
Water Source	**Before Buy-Back (MCM/year)**	**After Buy-Back (MCM/year)**	**Water Rights Bought Back (MCM/year)**
Surface	941	523	418
Groundwater	190	105	83.9
Total	**1,131**	**628**	**502**

4.2.1 PLAYERS

The players for the Water Demand Reduction game are the three largest irrigation water users in the basin. The first player is the Delicias Irrigation District 005 in the Rio Conchos. The second player is the Mexican Irrigation District 025, in the lower Rio Grande/Bravo basin. Finally, the third player, represented as a single player, is an aggregate of the largest irrigation districts in Texas below Falcon Reservoir (Watermaster Section 10), also in the lower basin. The approximate locations of the three players are shown in Figure 4-4.

District 005 was selected as a player since the management changes proposed under this scenario would be implemented there. The other players were selected because they have the largest water demands in the basin and are the most affected by the water management scenarios. Municipalities in the basin also have large demands, but not as large as the irrigation districts, and their water deliveries have priority over irrigation uses.

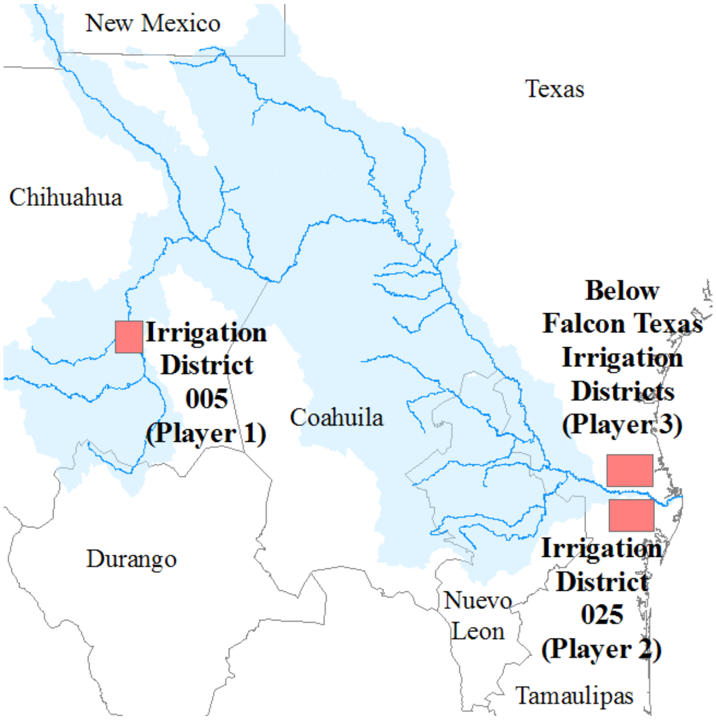

Figure 4-4 Location of the Three Players in the Cooperative Games for the Rio Grande/Bravo Basin

4.2.2 COALITION DESCRIPTIONS

The players in the Water Demand Reduction game may form a total of seven coalitions that range from individual or non-cooperative coalitions, to fully cooperative coalitions. In non-cooperative coalitions, the players act individually to maximize their benefits. In fully cooperative coalitions, all players act together to maximize their collective benefits, beyond what they could achieve acting individually. Players may also form partial coalitions consisting of subsets of players. Each possible coalition and the presumed actions taken by those coalitions are described below.

Coalition {1} This coalition represents Player 1, Irrigation District 005, acting alone. Irrigation District 005 has a total annual water demand of 1,131 MCM. Under this coalition, District 005 ensures their own delivery of water to satisfy their total demand.

Coalition {2} This non-cooperative coalition represents Player 2, Irrigation District 025, acting alone. Irrigation District 025 has an annual water demand of 1,127 MCM which is met through withdrawals from the Rio Grande/Bravo. In this coalition, Irrigation District 025 does not finance water buybacks in the Rio Conchos and attempts to meet their water demand with the available water.

Coalition {3} This coalition characterizes Player 3, Watermaster Section 10 (below Falcon reservoir), acting alone. Watermaster Section 10 is represented as a single player with an annual water demand of 647 MCM which is satisfied through withdrawals from the Rio Grande. Under this coalition, this player does not finance water buybacks in the Rio Conchos and attempts to meet their water demands with the water available in the Rio Grande.

Coalition {1, 2} District 005 and District 025 work cooperatively under this partial coalition. District 025 provides the investment to purchase 502 MCM of combined surface and groundwater water rights in District 005 (see Table 4-2), reducing District

005's demand for water. Due to physical losses in the system, as the water travels downstream, only about 20% of the water released from District 005 reaches the lower basin (Sandoval *et al*., 2008). Additionally, according to the 1944 Treaty, any water from the Rio Conchos reaching the Rio Grande is divided 1/3 to the U.S. and 2/3 to Mexico (IBWC, 1944). 418 MCM of surface water rights are purchased from District 005. District 025 is entitled to 56 MCM because of the system losses and treaty division. Only the surface water rights are available to the downstream players because there is no plan to pump the groundwater into the river.

Coalition {1, 3} District 005 and Watermaster Section 10 work cooperatively, with Watermaster Section 10 providing investment to purchase 502 MCM of surface and ground water rights, thus reducing District 005's overall demand for water (see Table 4-1). Due to physical losses and treaty obligations described above, Watermaster Section 10 is entitled to an additional 28 MCM/year of the 418 MCM of purchased surface water rights after accounting for the treaty division and the system losses. The groundwater portion of the water buybacks is not available to the Watermaster Section 10 because there is no plan to pump the groundwater into the river.

Coalition {2, 3} District 025 and Watermaster Section 10 cannot increase their benefits without including District 005. The water buybacks occur strictly in District 005. Since they are not in this coalition, District 005 may continue to use water at their non-cooperative rate, which leaves District 025 and Watermaster Section 10 with access to the same amount of water they receive under the non-cooperative solution.

Coalition {1, 2, 3} In the Grand Coalition, District 005, District 025 and Watermaster Section 10 all work cooperatively. Both District 025 and Watermaster Section 10 provide the investment to purchase 502 MCM of water rights, thus reducing District 005's overall demand for water. District 025 and Watermaster Section 10, are entitled to share the 418 MCM of surface water rights bought-back, 84 MCM/year after losses and treaty obligations. The downstream players do not have access to the groundwater rights bought-back because there is no plan to pump the groundwater and send it downstream, it remains in the aquifer.

4.2.3 CHARACTERISTIC FUNCTION UTILITY

In cooperative game theory, a characteristic function is calculated to express the value of a coalition. The characteristic function for the Water Demand Reduction game is based on the minimum delivery received by each of the game's players. The players are agricultural users who derive monetary benefit from water deliveries. A critical value to an irrigator may be their minimum delivery, the smallest annual amount that they will receive in a planning period, which may constrain their agricultural production.

Minimum deliveries for each player are determined for a simulation period, *N*. The minimum delivery, X_i^{min}, is defined for each player *i* for all time *t* over the period *N* as

$$\boldsymbol{X_i^{min}} = \underset{\boldsymbol{t \in N}}{\boldsymbol{Minimum}}(\boldsymbol{X_i^t}) \qquad \textbf{Equation 4-1}$$

where:

N	the total number of years in the simulation
X_i^t	delivery to player *i* at time *t*, *t* = 1,…, *N*

To calculate the characteristic functions for the coalitions, a value must be assigned to the water delivered to each coalition. Water sharing in the Rio Grande/Bravo is governed by allocation rules in various treaties and water sharing agreements between the U.S. and Mexico. The largest constraint on water sharing is the 1944 treaty in which the water flowing from the 6 tributaries in Mexico is divided 1/3 to the U.S. and 2/3 to Mexico once it reaches the main channel as described in Section 2.1.1 (IBWC, 1944). Due to this constraint, the volumes of water are not transferred between players proportionally. Any unit of water released from the Rio Conchos is immediately divided at the confluence of the Rio Grande/Bravo with 1/3 to the U.S. and 2/3 to Mexico. Due to this constraint, the cooperative games are created in monetary terms, rather than in volumes of water because money can be transferred proportionally among the players. Players negotiate for a share of the monetary benefits rather than for volumes of water.

In each simulation, each player receives a minimum water delivery, which is converted to a monetary value.

Literature outlines a few economic studies of water in the Rio Grande/Bravo basin. Characklis *et al.* (1999) and Scott *et al.* (2007) determined the price of water from data on water transferred from agricultural users to municipal users in the lower Rio Grande/Bravo and in the major tributary the Rio San Juan, respectively. Characklis *et al.* (2006) developed a demand function based on water availability in upstream reservoirs and water right prices for U.S. irrigators in the lower Rio Grande/Bravo valley. These values represent a user's willingness to pay for an increment of water (Young, 2005). While these are reasonable values for the price of water, they do not account factors such as government subsidies, agricultural profits or production costs to create a total value of water.

Monetary values for water delivered are based on previous economic analyses of the Rio Conchos basin (Gastélum, 2006 and Gastélum *et al*., 2009). In both studies, the authors estimated crop prices using a 4 year average of the latest available data, taking into account production costs that include land preparation, planting, fertilizers, pesticides, irrigation, insurance and harvesting. Profits from crops were determined as an average for the period of 1998-2001 and expressed in 2005 values as $63 million/year for all three irrigation districts in the Rio Conchos (Gastélum, 2006). This average profit was related to the average delivery volume of 731.8 MCM/year for the same period to all three irrigation districts (CONAGUA, 2008). The profit per unit of water delivered for

District 005 in the Rio Conchos is \$86,000/MCM (U.S. dollars) and is set as the value of water for District 005 for the game analysis.

Similar data on crop production for the lower basin irrigation districts was not available, so an assumption is made that the irrigation districts in the lower basin, District 025 and Watermaster Section 10, value their water deliveries at the same rate as District 005. This is a reasonable assumption because the operating costs and agricultural profits are similar across the border (Personal Communication, Engineer Caballero, President, Unidad Conchos Water Users' Association, May 2005). For the Water Demand Reduction game, all of the players value water deliveries at \$86,000/MCM.

4.2.4 CHARACTERISTIC FUNCTION CALCULATIONS

This section describes how the characteristic functions are calculated for each coalition in the Water Reduction Game in the Rio Grande/Bravo. The characteristic functions are the value of the coalition and are used in the game theory calculation described in Chapter 5.

4.2.4.1 Non-Cooperative Coalitions

{1}, {2} and {3} In each of these coalitions, each player, $i = 1$ to 3, receives a minimum delivery, min_D_i (MCM), which they value at a rate of p_D (\$/MCM). The characteristic values for the non-cooperative coalitions, $v(1)$, $v(2)$, $v(3)$, are calculated as

District 005- $p_D*min\_D_1$ **Equation 4-2**

District 025 - $p_D*min\_D_2$ **Equation 4-3**

Watermaster Section 10 - $p_D*min\_D_3$ **Equation 4-4**

4.2.4.2 Partial Coalitions

{1, 2} For the partial coalition of Districts 005 and 025, District 025 purchases water rights, $V_{1,2}$ (MCM), from District 005 at a price, $p_{1,2}$ (\$/MCM). District 005 receives a modified minimum delivery volume, $min\_D_1' = min\_D_1 - V_{1,2}$ (MCM). District 025 receives a modified minimum delivery volume, min_D_2' (MCM). The modified minimum delivery, min_D_2', is not equal to the non-cooperative minimum delivery plus the volume bought back or $min\_D_2 + V_{1,2}$, due to the 1944 Treaty water division and the system losses described in Section 4.2.2. The monetary values to Districts 005 and 025 are calculated as

District 005 - $p_D*min\_D_1' + p_{1,2}*V_{1,2}$ **Equation 4-5**

District 025 - $p_D*min\_D_2' - p_{1,2}*V_{1,2}$ **Equation 4-6**

The characteristic value of this coalition, $v(1,2)$, is the sum of equations 4-5 and 4-6.

{1, 3} For the partial coalition of Districts 005 and Watermaster Section 10, Watermaster Section 10 purchase water rights, $V_{1,3}$ (MCM), from District 005 at a price,

$p_{1,3}$ (\$/MCM), which may be different from $p_{1,2}$. District 005 receives a modified average minimum volume, min_D_1' (MCM). Watermaster Section 10 receives a modified minimum delivery of min_D_3' (MCM). It should be noted that the modified delivery volume, min_D_3', is not equal to the non-cooperative minimum delivery volume and the volume bought back from Player 1 ($min\_D_3+V_{1,3}$) because of the large system losses and the 1944 Treaty division of water from the Rio Conchos to the U.S. and Mexico. Thus, the monetary values to Districts 005 and Watermaster Section 10 are

District 005 - $p_D*min\_D_1' + p_{1,3}*V_{1,3}$ **Equation 4-7**

Watermaster Section 10 - $p_D*min\_D_3' - p_{1,3}*V_{1,3}$ **Equation 4-8**

The characteristic value for this partial coalition, $v(1,3)$ is the sum of equations 4-7 and 4-8.

{2, 3} Under this partial coalition, District 025 and Watermaster Section 10 Districts cannot increase their benefits without inclusion of District 005. The value to each player in this coalition is the same as the non-cooperative values.

District 025 - $p_D*min\_D_2$ **Equation 4-9**

Watermaster Section 10 - $p_D*min\_D_3$ **Equation 4-10**

The characteristic function, $v(2,3)$ is the sum of the non-cooperative equations 4-9 and 4-10.

4.2.4.3 Grand Coalition

{1, 2, 3} All players cooperate under the Grand Coalition. District 025 and Watermaster Section 10 each finance part of the water right buy-back in DR005. District 025 receives a modified minimum delivery of min_D_2'' (MCM), and in turn, they compensate District 005 for a portion of the water buy-back volume, $V_{1,2}$ (MCM). Watermaster Section 10 receives a modified minimum delivery of min_D_3'' (MCM) and compensates District 005 for a portion of the water rights bought back, $V_{1,3}$ (MCM). District 005 receives compensation from both District 025 and the Watermaster Section 10 and a modified minimum delivery of min_D_1''. Thus, the monetary values to District 005, District 025 and Watermaster Section 10 are

District 005 - $p_D * min\_D_1'' + p_{1,2} * V_{1,2} + p_{1,3} * V_{1,3}$ **Equation 4-11**

District 025 - $p_D * min\_D_2'' - p_{1,2} * V_{1,2}$ **Equation 4-12**

Watermaster Section 10 - $p_D * min\_D_3'' - p_{1,3} * V_{1,3}$ **Equation 4-13**

The characteristic value of the Grand Coalition, $v(1,2,3)$ is calculated as the sum of equations 4-11 through 4-13.

4.2.5 PERFORMANCE MEASURES

The water management scenarios considered here were developed to increase water availability to water users in the Rio Grande/Bravo basin (Sandoval *et al*., 2008). To determine if the Water Demand Reduction game improves water availability to each player, a set of performance metrics were calculated. The average delivery, $\bar{X}_i$, for player *i* in a period *N*, was calculated as

$$\boldsymbol{\overline{X_i}} = \frac{\sum_{t=1}^{N} X_i^t}{N} \qquad \textbf{Equation 4-14}$$

where:

N	the total number of simulation periods
X_i^t	delivery to player *i* at time *t*

In addition to the average water delivery, performance measures are used to characterize the performance of a water management scenario. The changes in water allocation caused by the water management decisions are evaluated using performance measures, which capture more of the distribution of the performance, in addition to the characteristic function values, which only captures the minimum or worst case, performance.

For the Water Demand Reduction game the performance measures of Vulnerability, Resilience and Reliability were calculated to provide information about a player's severity of water shortages, the player's ability to recover from water shortages and the reliability of water deliveries (Sandoval – Solis *et al*., 2008; Loucks and van Beek 2005).

A deficit, D_i^t, is defined as any delivery X_i^t to player i in any year t, that is less than the player's demand at time t, $Demand_i^t$. A deficit is calculated as follows:

$$\boldsymbol{D_i^t = \begin{cases} 0 & if\ X_i^t = Demand_i^t \\ Demand_i^t - X_i^t & if\ X_i^t < Demand_i^t \end{cases}}$$ **Equation 4-15**

Reliability for player i is the probability that a deficit does not occur over the period of analysis (Klemes *et al*., 1981; Hashimoto *et al*., 1982; McMahon *et al*., 2006)

$$\boldsymbol{Reliability_i = \frac{n_{D_i^t=0}}{N}}$$ **Equation 4-16**

where:

$n_{D_i^t=0}$ the number of zero deficit years for player i for all years t in the simulation period

Resilience, a measure of the rate of system recovery following a deficit period, is the probability that a year with no deficit occurs immediately after a year with a deficit (Hashimoto *et al*., 1982).

$$\boldsymbol{Resilience_i} = \frac{\#\ \boldsymbol{of\ times\ D_i^t{=}0\ follows\ D_i^t{>}0}}{\boldsymbol{n_{D_i^t>0}}} \qquad \textbf{Equation 4-17}$$

where:

D_i^t the deficit occurring in year *t* to player *i*

$n_{D_i^t > 0}$ the total number of deficits for player *i* over the simulation period

Vulnerability, the expected value of the annual deficits, or the average deficit (Hashimoto *et al.*, 1982), is calculated as a percent of player *i*'s total demand as follows (McMahon *et al.*, 2006):

$$\boldsymbol{Vulnerability_i} = \frac{\frac{\sum_{\forall D_i^t>0} \boldsymbol{D_i^t}}{\boldsymbol{n_{D_i^t>0}}}}{\boldsymbol{demand_i}} \qquad \textbf{Equation 4-18}$$

where:

demand$_i$ annual water demand for player *i*

5 RESULTS

The cooperative game theory framework described in the previous chapters has been applied to a water management scenario for the transboundary Rio Grande/Bravo. The Water Demand Reduction game is calculated for a 60 year period. To evaluate the effect of the compensation scheme in the Water Demand Reduction game, a new compensation scheme with outside funding was devised. In addition to evaluating the compensation scheme, a period of drought was selected for comparison with the 60 year analysis period. This drought analysis is done to determine the outcomes of the game (1) over a long-term simulation period, and (2) over a drought period. The game is first calculated for the long-term 60 year period and is described in Section 5.1. The second game with the compensation analysis is presented in Section 5.2, and finally, the drought analysis is described in Section 5.3.

5.1 Long-Term Cooperative Game

The water rights buy-back scenario described above is used for the non-cooperative coalitions, representing the status-quo scenario. District 005's water demand is set at 1,131 million cubic meters per year (MCM/year) for the non-cooperative coalitions. Watermaster Section 10's demand is set 647 MCM/year, the value used in the TCEQ Water Availability Model (WAM) (TCEQ, 2005), representing the maximum for 1989-2002 (Brandes, 2004). The demand for District 025 is set at 1,127 MCM, the median delivery over 1960 to 2004 (IBWC, 2009). This district does not have a set water right and the delivery has been varied historically (Figure 4-3). The coalitions were simulated in the Rio Grande/Bravo model using naturalized inflow data for the 60-year historical period 1940-2000 and the demands are assumed to be constant over the simulation period.

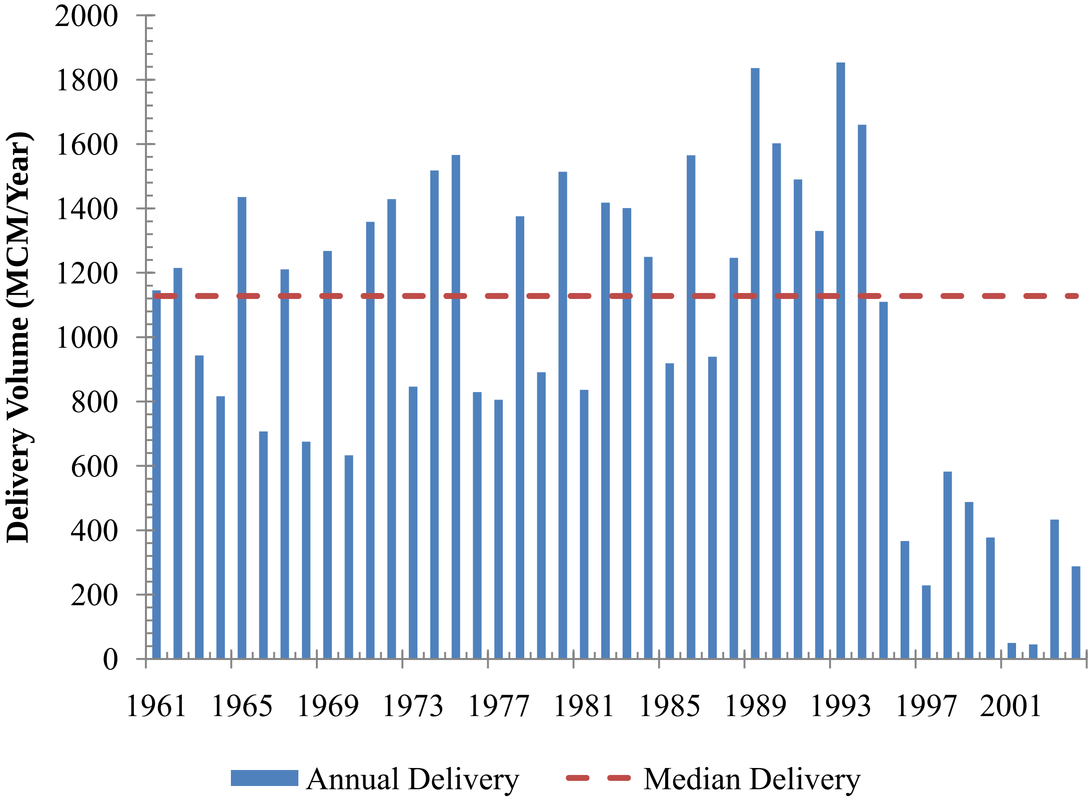

Figure 5-1 Historical Deliveries and Median Delivery to Irrigation District 025 in the Lower Rio Grande/Bravo (IBWC, 2009)

The characteristic functions and performance criteria were calculated for the 60-year period for each player in the game. The value of water deliveries, p_D, to District

005, District 025, and Watermaster Section 10, is \$86,000/MCM. The value of compensation for water rights buy backs in District 005 from District 025, $p_{1,2}$, and Watermaster Section 10, $p_{1,3}$, is \$86,000/MCM, assuming that District 005 would accept, as minimum compensation, the potentially lost revenue from the bought-back water rights. The characteristic values for the game are described in detail in the following section.

5.1.1 CHARACTERISTIC FUNCTIONS

{1} In this coalition, District 005 receives an average of 88% of their demand. The minimum delivery to this player is 74 MCM. Given this minimum delivery, the value of this coalition is $v(1)$ = \$6.4 million/year (Table 5-1). Under this non-cooperative coalition District 005 has a long-term average deficit or Vulnerability of 38%, a Reliability of 68%, and a Resilience of 32% (Table 5-2).

{2} Without cooperating, District 025 receives an average of 89% of their total annual demand and a minimum delivery of 400 MCM. The value of this coalition is $v(2)$ = \$34.4 million/year based on their minimum delivery (Table 5-1). District 025 has a Vulnerability of 30%, a Reliability of 63%, and a Resilience of 32% (Table 5-2).

{3} Watermaster Section 10 receives an average of 95% of their annual demand and a minimum delivery of 356 MCM. The value of this coalition is $v(3)$ = \$30.7 million/year

(Table 5-1). Under the non-cooperative coalition, Watermaster Section 10 has a Vulnerability of 20%, Reliability of 75%, and a Resilience of 33% (Table 5-2).

Table 5-1 Demands, Deliveries, and Characteristic Values for Non-Cooperative Coalitions {1}, {2}, {3}

Player	Category	Unit	Amount
District 005	Annual Demand	MCM	1131
	Minimum Delivery	MCM/year	74
	Coalition Value	**$Million/year**	**6.4**
District 025	Annual Demand	MCM	1127
	Minimum Delivery	MCM/year	400
	Coalition Value	**$Million/year**	**34.4**
Watermaster Section 10	Annual Demand	MCM	647
	Minimum Delivery	MCM/year	356
	Coalition Value	**$Million/year**	**30.7**

Table 5-2 Performance Criteria for the non-cooperative coalitions {1}, {2}, {3}

Player	Average Annual Delivery (%)	Vulnerability (%)	Reliability (%)	Resilience (%)
District 005	88	38	68	32
District 025	89	30	63	32
Watermaster Section 10	95	20	75	33

{1, 2} Under this coalition, District 005's demand is reduced to 628 MCM and they receive, on average, 98% of their demand and have a minimum water delivery of 222

MCM/year (Table 5-3). By reducing their overall demand for water, District 005 gets an increase in both their average annual deliveries and their minimum delivery. Their minimum delivery is increased by 148 MCM/year or 10% (Figure 5-2). The increase in minimum delivery may be due to the fact that, with a reduced water demand, the storage in both surface reservoirs and the groundwater are slightly increased, ensuring better deliveries over time. This idea is reflected in the changes in the water performance measures.

District 005 has a considerable increase in the performance of their water deliveries. In addition to the increased minimum delivery, District 005 has decreased their Vulnerability (long-term average deficit) by 2%, increased their Reliability by 25% and increased their Resilience by 43% (Table 5-2). Each of these performance metrics demonstrates improvement in the delivery to District 005 under this coalition(Figure 5-2).

By working cooperatively with District 005 under this coalition, District 025 receives an improvement in their water deliveries. District 025 receives an average of 93% of their 1124 MCM annual demand and a minimum delivery of 519 MCM which is an increase of 119 MCM/year over their non-cooperative delivery (Figure 5-3) This increased minimum delivery increases their water delivery value to $44.6 million (Table 5-3). Due to this cooperation, District 025 has increased both Reliability and Resilience by 14% (Figure 5-3). The Vulnerability does not change, but there is an improvement in Resilience, so the system recovers more quickly from deficits than before. The increase in Reliability means that District 025 has a lower probability of deficits in the simulation period.

The increases in District 025's Reliability and Resilience indicate an improved performance in water deliveries (Figure 5-3). The small changes in the performance measures is likely a result of the small delivery volumes from the water buy-backs, due to the system losses and the treaty division. Under the 1944 Treaty, the water from the Rio Conchos is split with 1/3 to the U.S. and 2/3 to Mexico and of that volume only 20% reaches the lower basin due to the large system losses (see Section 4.2.2). The value of this coalition is the sum of equations 4-5 and 4-6 and is $v(1, 2)$ = \$63.7 Million (Table 5-3).

Table 5-3 Demands, Deliveries, and Values for Coalition {1, 2}

Player	**Category**	**Unit**	**Amount**
District 005	Annual Demand	MCM/year	628
	Minimum Delivery	MCM/year	222
	Value of Delivery	\$Million/year	19.1
	Value of Compensation	\$Million/year	43.3
District 025	Annual Demand	MCM/year	1127
	Minimum Delivery	MCM/year	519
	Value of Delivery	\$Million/year	44.6
	Value of Compensation	\$Million/year	-43.3
Coalition Value		**\$Million/year**	**63.7**

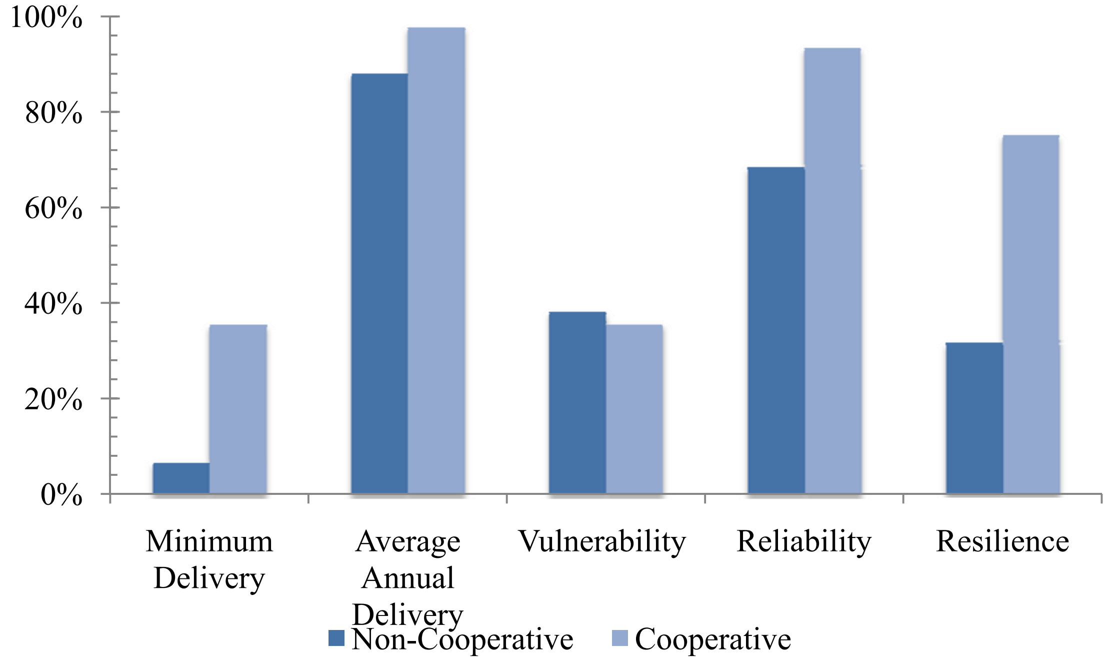

Figure 5-2 Comparison of Performance Metrics for District 005 under the Partial Cooperative Coalition {1, 2} and their Non-Cooperative Coalition {1}

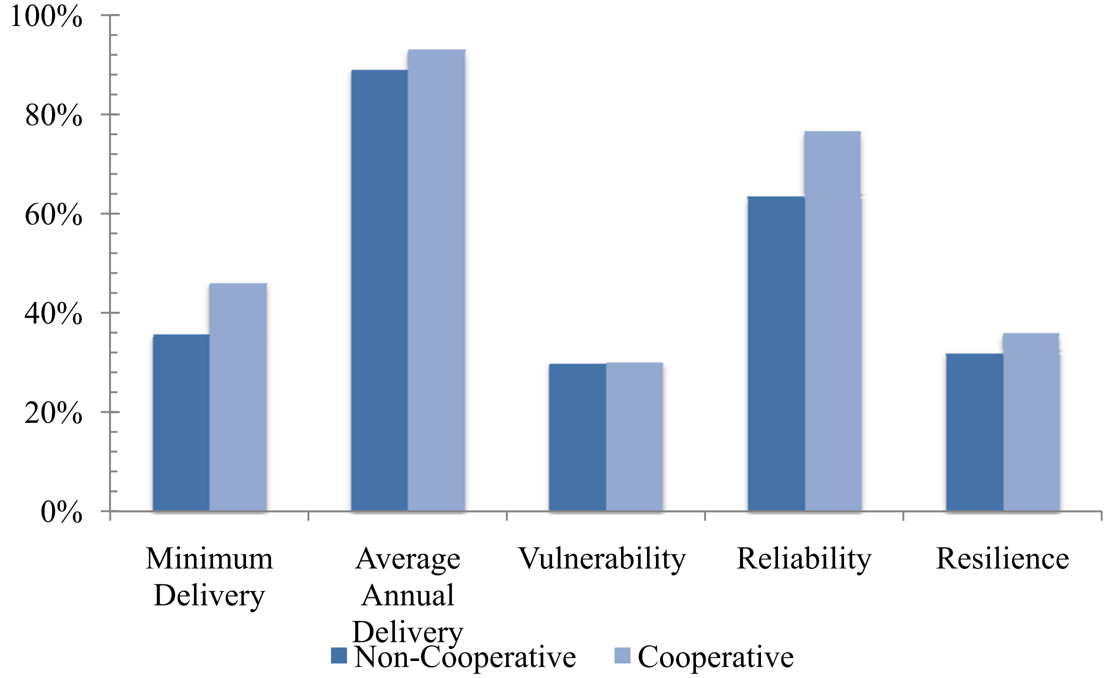

Figure 5-3 Comparison of Performance Metrics for District 025 under the Partial Cooperative Coalition {1, 2} and their Non-Cooperative Coalition {2}

{1, 3} In this partial coalition, District 005 and Watermaster Section 10 work cooperatively to increase their benefits beyond their non-cooperative values. District 005's demand is reduced to 628 MCM and they receive an average of 98% or their annual demand. District 005 has an increased minimum delivery of 222 MCM. The performance measures for District 005 are the same as under the coalition {1, 2} with a decrease in vulnerability and an increase in reliability and resilience indicating improved water deliveries (Figure 5-2).

Watermaster Section 10 receives 97% of their annual demand and an increased minimum delivery of 393 MCM (Table 5-4). District 005 is compensated \$43.3 million/year from Watermaster Section 10 for the water rights which are bought back (Table 5-4). Under the non-cooperative coalition, Watermaster Section 10 was receiving a minimum delivery of 55% which is increased to 61% under this coalition. Watermaster 10 has less than 5% change in all performance measures (Figure 5-4), due to the limited increase in water deliveries under this coalition. Although 502 MCM are bought-back from District 005, Watermaster Section 10 is only entitled to 28 MCM after the treaty division and the system losses. Additionally, that 28 MCM is only delivered in years when there is sufficient water in the system to cover the other water demands in the basin. The value of this coalition is the sum of Equations 4-7 and 4-8 and is expressed in characteristic form as $v(1, 3)$ = \$52.9 million/year (Table 5-4).

Table 5-4 Demands, Deliveries, Values for Coalition {1, 3}

Player	**Category**	**Unit**	**Amount**
District 005	Annual Demand	MCM	628
	Minimum Delivery	MCM/year	222
	Value of Delivery	$Million/year	19.1
	Value of Compensation	MCM	43.3
Watermaster Section 10	Annual Demand	$Million/year	646
	Minimum Delivery	MCM	393
	Value of Delivery	$Million/year	33.8
	Value of Compensation	$Million/year	-43.3
Coalition Value		$Million/year	**52.9**

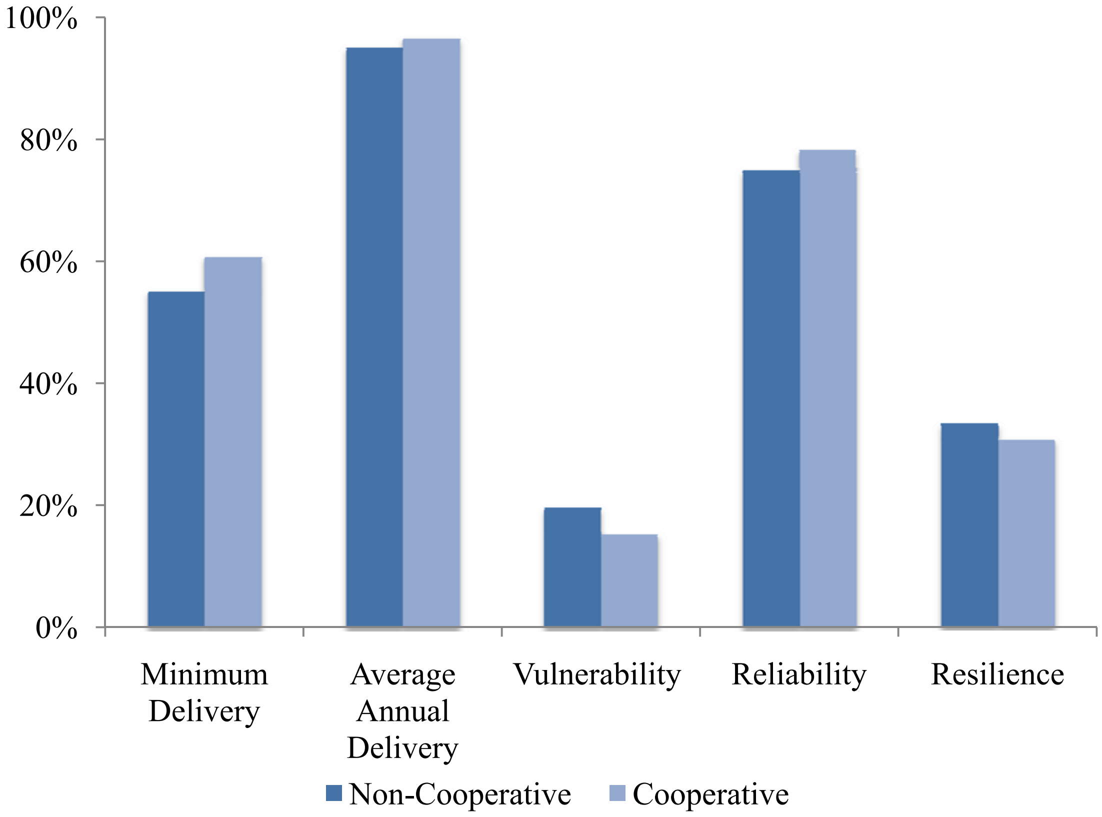

Figure 5-4 Comparison of Performance Metrics for Watermaster Section 10 under the Partial Cooperative Coalition {1, 3} and their Non-Cooperative Coalition {3}

{2, 3} District 025 and the Texas Irrigators cannot increase their benefits under this coalition. The coalition value is equal to the sum of the non-cooperative solution (Equations 4-9 and 4-10), $v(1, 3)$ = \$65.1 million/year (Table 6-2).

{1, 2, 3} The Grand Coalition represents all three players working to cooperatively increase their benefits. District 025 and Watermaster Section 10 share equally in the payment of compensation to District 005 for water buybacks (Table 5-5). District 005 has the greatest improvement in water delivery under this coalition (Table 5-6). By joining this coalition, District 005 has a reduced demand for water, but they get more reliable deliveries for the reduced demand. District 025 has increased performance, but not as large as District 005's. Their largest improvement lies in the increased Reliability and ability to recover from deficits (Resilience). Watermaster Section 10 has the smallest improvement of all players in the coalition. This minimal improvement can be attributed to the small amount of additional water that they receive after the system losses and the treaty division. The value of this coalition is the sum of Equations 4-11 through 4-13, $v(1 ,2 3)$ = \$97.5 million/year (Table 5-5).

Table 5-5 Demands, Deliveries, and Values for the Grand Coalition {1, 2, 3}

Player	Category	Unit	Amount
District 005	Annual Demand	MCM	628
	Minimum Delivery	MCM/year	222
	Value of Delivery	$Million/year	19.1
	Value of Compensation	$Million/year	43.3
District 025	Annual Demand	MCM/year	1127
	Minimum Delivery	MCM/year	519
	Value of Delivery	$Million/year	44.6
	Value of Compensation	$Million/year	-21.7
Watermaster Section 10	Annual Demand	$Million/year	646
	Minimum Delivery	MCM	393
	Value of Delivery	$Million/year	33.8
	Value of Compensation	$Million/year	-21.7
Coalition Value		$Million/year	**97.5**

Table 5-6 Performance Criteria for Coalition {1, 2, 3} Including Change in Performance over the Non-Cooperative Solution

Player	**Average Annual Delivery (%)**	**Vulnerability (%)**	**Reliability (%)**	**Resilience (%)**
District 005	+10	-2	+25	+43
District 025	+4	0	+14	+14
Watermaster Section 10	+2	-5	+3	-2

5.1.2 COOPERATIVE GAME ANALYSIS

The characteristic values for the Water Reduction Game were calculated for each coalition ranging from non-cooperative to fully cooperative Grand Coalitions. These characteristic values are used in a cooperative game analysis to determine the value of cooperation and provide the players the opportunity to negotiate and divide the benefits of that cooperation. This section describes the results of the cooperative game analysis.

5.1.2.1 The Core

The characteristic values for the coalitions under the Water Demand Reduction game for the 60-year long-term period are displayed in Table 5-7. The characteristic values are the monetary value of the minimum water delivery to each player in the coalition over the 60-year period as described in Section 4.2.5. These characteristic values are used to determine the existence of the Core. The Core defines a set of solutions that satisfies individual and collective rationality, or in other words, a set of solutions or allocations which each player is willing to accept from negotiation (see Section 3.2). The Core of the Water Demand Reduction game is defined by the bounds of allocations, Ω_i, to each player *i* as:

$$\Omega_1 \geq v(1) = 6.4$$

$$\Omega_1 \leq v(1,2,3) - v(2,3) = 32.6$$

$$\Omega_2 \geq v(2) = 34.4$$

$$\Omega_2 \leq v(1,2,3) - v(1,3) = 44.7$$

$$\Omega_3 \geq v(3) = 30.7$$

$$\Omega_3 \leq v(1,2,3) - v(1,2) = 33.8$$

Table 5-7 Characteristic Values of the Water Reduction Game Coalitions for the 60-year Period

Coalition	**Characteristic Value ($Million/year)**
v(1)	6.4
v(2)	34.4
v(3)	30.7
v(1, 2)	63.8
v(1, 3)	52.9
v(2, 3)	65.0
v(1, 2, 3)	97.6

If there are more than 3 players, as in the Syr Darya game (Appendix), then the Core cannot be displayed on a simplex. The Water Demand Reduction game involves only 3 players so the Core may be drawn on a simplex as shown in Figure 5-5. The overall height of the simplex is $97.6 million, corresponding to the value of the Grand Coalition. The Core is bounded by the minimum value that a single player is willing to accept and the maximum value that the other players in the coalition are willing to give that player under the Grand Coalition.

The Core for the Water Demand Reduction game exhibits some interesting characteristics. One interesting characteristic is that District 005, Player 1, has a negotiation range from $19.1 million to $32.6 million. The non-cooperative solution for District 005 is $6.4 million, but according to the Core, the lowest that District 005 will ever receive is $19.1 million. This minimum value corresponds to the upper right corner of the Core. This increased lower bound is due to the other players' dependence on District 005 for cooperation. Without the cooperation of District 005, a game does not exist and the other players cannot improve their allocation.

Another interesting characteristic of the Core is that Player 3, Watermaster Section 10, has a very narrow negotiation range from $30.7 million to $33.8 million. This narrow range demonstrates that this player brings very little additional benefit to the Grand Coalition because of the small improvement in their allocation as described in Section 5.1.1. Watermaster Section 10's stability in this game will be examined in Section 5.1.2.3.

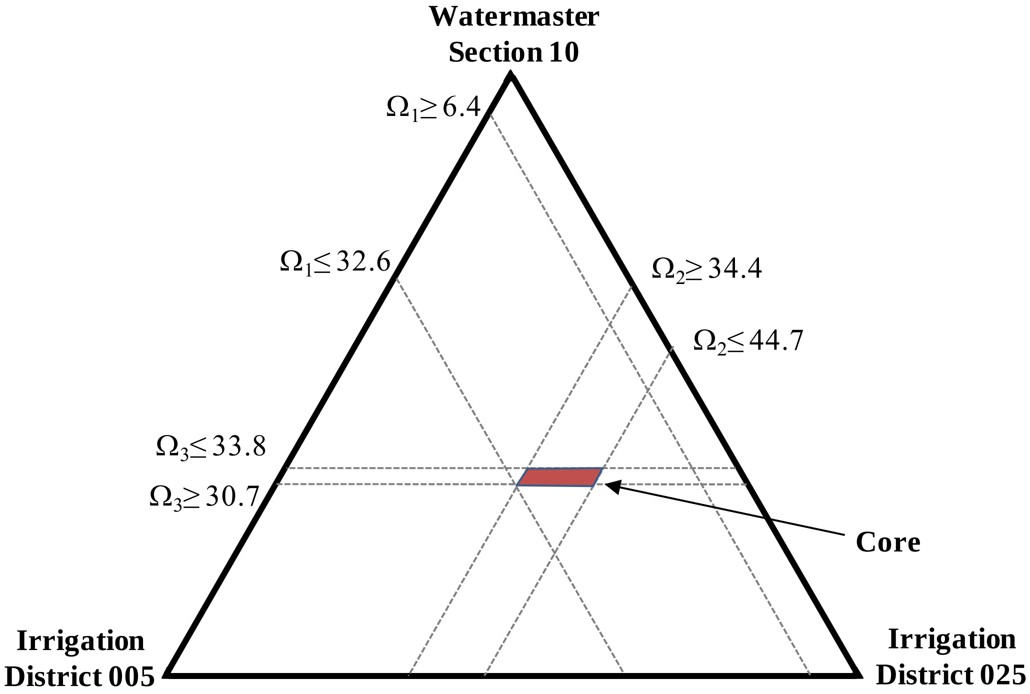

Figure 5-5 The Core of the Water Reduction Game for the 60-year period

5.1.2.2 Allocation Methods

The Core defines a set of possible allocations to each player from the value of the Grand Coalition. To select a single allocation, two methods are employed in this research. The first method is the Shapley value, which selects a point in the Core based on the marginal contribution of each player to the Grand Coalition, or in other terms, each player receives an allocation of the coalition gains proportional to their contribution to the coalition gains (Table 5-8). For this game, the Shapley value is calculated as $\mathbf{\Omega}_1$ = \$22 million, $\mathbf{\Omega}_2$ = \$42 million and $\mathbf{\Omega}_3$ = \$34 million.

Table 5-8 Calculation of the Shapley Allocation

Permutation	**Unit**	**Marginal Contribution of Player to the Coalition** **1**	**2**	**3**
123	Million $	6	57	34
132	Million $	6	45	47
213	Million $	29	34	34
231	Million $	33	34	31
312	Million $	22	45	31
321	Million $	33	34	31
Shapley Allocation	**Million $**	**21.6**	**41.7**	**34.4**
Percent of Profit	%	22	42	35

The Core represents the gains of the whole coalition which are the sum of each coalition player's use of the minimum delivery volume for agricultural profit. The individual profits are summed and the gains divided according to the allocation method. In the Grand Coalition, District 005 has a minimum delivery value of $19 million (see Table 5-9) but can negotiate for an additional $3.0 million from the Grand Coalition. District 025 has a minimum delivery value of $44.6 million but must share $2.6 million of this value to the coalition for cooperation. District 025 shares $2.6 million of their coalition allocation of $42 million which is still larger than their non-cooperative value of $34.4 million. Watermaster Section 10 has a minimum delivery value of $33.8 million but receives an additional $0.4 million from the Core for an allocation of $34.4. From the overall profits of cooperation, these are the values that each player could expect to receive annually as a result of negotiation. As can be seen from the results, each player can expect to receive an increase over their non-cooperative values (Table 5-9).

Another method for determining an allocation from the Core is the Nucleolus. The Nucleolus is based on minimizing the least satisfied coalition member (Schmeidler, 1969), meaning the Nucleolus minimizes the greatest difference in coalition allocations and a player's minimum allocation or increases the smallest allocation. The Nucleolus allocations, $\boldsymbol{\Omega}_i$ to each player $i = 1$ to N, where N equals the total number of players, are calculated as a linear programming problem minimizing the excesses, e, as follows:

$$Minimize\ e$$

Subject to:

$$e \le \Omega_1 - 6.4$$

$$e \le \Omega_2 - 34.4$$

$$e \le \Omega_3 - 30.7$$

$$e \le \Omega_1 + \Omega_2 - 63.8$$

$$e \le \Omega_1 + \Omega_3 - 52.9$$

$$e \le \Omega_2 + \Omega_3 - 65.0$$

$$\Omega_1 + \Omega_2 + \Omega_3 = 97.6$$

Under the Shapley allocation, District 025 had to share \$2.6 million of their coalition allocation from their \$42 million water allocation, making them the least satisfied player. The Nucleolus increases District 025's allocation to \$43.4 by reducing Watermaster Section 10's allocation to \$32.2 million. Under the Nucleolus allocation, as with the Shapley allocation, each player receives an increased allocation over their non-cooperative values (Table 5-9).

Table 5-9 Comparison of Allocations to Players in the Water Reduction Game

Player	**Non-Cooperative Allocation ($million/year)**	**Shapley Allocation ($million/year)**	**Nucleolus Allocation ($million/year)**
District 005	6.40	21.6	22.2
District 025	34.4	41.7	43.4
Watermaster Section 10	30.7	34.4	32.2

5.1.2.3 Stability

Both the Shapley and Nucleolus provide an allocation that improves each player's value above their Non-Cooperative allocations. Each allocation method is based on mathematical concepts for a 'fair' allocation. To evaluate the stability of the allocation solutions, the Gately equation, or the propensity to disrupt, is used to measure a player's ability to harm other players by leaving the coalition. The propensity to disrupt compares a player's loss from leaving the coalition to the loss of the remaining coalition members. If a player has a large propensity to disrupt compared to the other players, then their allocation should be improved to ensure that they do not leave the coalition. The propensity to disrupt is measured relative to each player in a coalition and should be close to zero if a player is satisfied. The propensity to disrupt for each player under both the Shapley and Nucleolus allocations are displayed in Table 5-10.

Table 5-10 Each Player's Propensity to Disrupt for the Shapley and Nucleolus Allocations

Player	Shapley Allocation	Nucleolus Allocation
District 005	0.7	0.7
District 025	0.4	0.2
Watermaster Section 10	-0.2	0.9

District 005 has the same propensity to disrupt under both the Shapley and Nucleolus allocation schemes. This is due to the fact that both allocations are roughly equal (Table 5-9). Changes in propensity to disrupt can be seen in District 025 and Watermaster Section 10. Watermaster Section 10 has a negative propensity to disrupt, indicating that they would lose more by leaving the coalition compared to the other players. However, under the Nucleolus allocation, when District 005 receives a decreased allocation, their propensity to disrupt approaches one. Conversely, Watermaster 10's propensity to disrupt is increased from the Shapley under the Nucleolus.

All players, under both allocation schemes, have propensities to disrupt under one. This means that the loss to the other coalition members by them leaving the coalition is less than what they would lose leaving the coalition. The loss to District 025 and Watermaster Section 10 is small compared to the loss incurred by District 005 leaving the Grand Coalition. Either allocation method would create a suitable starting point for negotiation among the players.

5.2 Compensation

The Water Demand Reduction game assumes that the downstream players fully fund the water buy-backs in District 005. However, the losses in the Rio Grande/Bravo are large as water travels from the Rio Conchos to the lower part of the basin. Eighty percent of the water released from the Rio Conchos basin is lost before reaching the users in the lower basin (Sandoval *et al*., 2008). Due to these large losses the compensation value from the lower basin players to District 005 was scaled back based on their actual deliveries. For analysis, an assumption was made that District 005 would still be compensated for the 502 MCM of water rights bought back, but District 025 and Watermaster Section 10 would only compensate District 005 for the portion of water which they receive. A further assumption is made that the remainder of the compensation would be paid by Mexico's Comisión Nacional del Agua (CONAGUA).

5.2.1 COALITIONS

CONAGUA provides compensation to District 005 in this analysis but they are not considered a player in the game because they do not receive an allocation of the benefits. The coalitions remain the same as described in Section 4.2.2 but the calculation for the partial coalitions with District 005 and the grand coalition change. Under these coalitions, the compensation has been changed to reflect the payment from CONAGUA to District 005. The general calculations for these coalitions are described below.

{1, 2} For the partial coalition of Districts 005 and 025, District 025 purchases a fraction of the water rights, $V_{1,2}$ (MCM), from District 005 at a price, $p_{1,2}$ ($/MCM). The fraction of water rights purchased by District 025, $V_{1,2}$, is equal to the amount that is delivered to them after accounting for the 1944 Treaty division and the system losses. CONAGUA purchases the remaining water rights, V_{MX} (MCM), at a price p_{MX} ($/MCM). District 005 receives a modified minimum delivery volume, $min\_D_1' = min\_D_1 - V_{1,2}$ (MCM). District 025 receives a modified minimum delivery volume, min_D_2' (MCM). The monetary values to Districts 005 and 025 are calculated as

District 005 - $p_D * min\_D_1' + p_{1,2} * V_{1,2} + p_{MX} * V_{MX}$ **Equation 5-1**

District 025 - $p_D * min\_D_2' - p_{1,2} * V_{1,2}$ **Equation 5-2**

The characteristic value of this coalition, $v(1,2)$, is the sum of equations 5-1 and 5-2.

{1, 3} For the partial coalition of Districts 005 and Watermaster Section 10, Watermaster Section 10 purchase a fraction of the water rights, $V_{1,3}$ (MCM), from District 005 at a price, $p_{1,3}$ ($/MCM). The volume of water rights that Watermaster Section 10 purchases from District 005, $V_{1,3}$, is equal to their volume of delivery after accounting for the 1944 Treaty division and the large system losses. CONAGUA purchases the remaining water rights, V_{MX} (MCM), at a price p_{MX} ($/MCM). District 005 receives a modified average minimum volume, min_D_1' (MCM). Watermaster Section 10 receives a modified minimum delivery of min_D_3' (MCM). The monetary values to Districts 005 and Watermaster Section 10 are

District 005 -	$p_D * min\_D_1' + p_{1,3} * V_{1,3} + p_{MX} * V_{MX}$	**Equation 5-3**
Watermaster Section 10 -	$p_D * min\_D_3' - p_{1,3} * V_{1,3}$	**Equation 5-4**

The characteristic value for this partial coalition, $v(1,3)$ is the sum of equations 5-3 and 5-4.

{1, 2, 3} All players cooperate under the Grand Coalition. District 025 and Watermaster Section 10 each finance part of the water right buy-back in DR005. District 025 receives a modified minimum delivery of min_D_2'' (MCM), and in turn, they compensate District 005 for a portion of the water buy-back volume, $V_{1,2}$ (MCM). Watermaster Section 10 receives a modified minimum delivery of min_D_3'' (MCM) and compensates District 005 for a portion of the water rights bought back, $V_{1,3}$ (MCM). District 005 is compensated for the remaining fraction of the water rights V_{MX} (MCM), by CONAGUA, at a price p_{MX} (\$/MCM). District 005 receives compensation from CONAGUA, District 025 and the Watermaster Section 10 and a modified minimum delivery of min_D_1''. The monetary values to District 005, District 025 and Watermaster Section 10 in the Grand Coalition are

District 005 - $p_D * min\_D_1'' + p_{1,2} * V_{1,2} + p_{1,3} * V_{1,3} + p_{MX} * V_{MX}$ **Equation 5-5**

District 025 - $p_D * min\_D_2'' - p_{1,2} * V_{1,2}$ **Equation 5-6**

Watermaster Section 10 - $p_D * min\_D_3'' - p_{1,3} * V_{1,3}$ **Equation 5-7**

The characteristic value of the Grand Coalition, $v(1,2,3)$ is calculated as the sum of equations 5-5 through 5-7.

5.2.2 RESULTS

The characteristic functions for the Water Reduction Game with the inclusion of CONAGUA were calculated in the same manner described in Section 5.1.1. The coalitions that do not include compensation from CONAGUA do not change under this scheme. The water deliveries and compensation for each of the non-cooperative coalition ({1}, {2}, and {3}) are the same as shown in Table 5-1 in Section 5.1.1. The water deliveries and compensation values for the partial coalition of District 025 and Watermaster Section 10, {2, 3}, do not change in this analysis and are equal to the sum of their non-cooperative values shown in Table 5-1. The performance measures do not change from the long-term analysis to this compensation analysis and therefore will not be discussed in this analysis.

In this analysis of the compensation scheme, an assumption is made that the lower basin players, District 025 and Watermaster Section 10, compensate District 005 for only a portion of water buy-backs while CONAGUA pays the difference. District 025 compensates District 005 for 12% of the buy-back volume because this percentage is equal to the two-thirds of the 20% volume delivery accounting for system losses and for the 1944 Treaty division of Rio Conchos water to Mexico. Table 5-11 displays the amount that District 005 receives in compensation for the water buy-backs. Also shown in Table 5-11 are the amounts which District 025, Watermaster Section 10, and CONAGUA pay to District 005 under the various coalition structures.

Table 5-11 Compensation Values for Water Buy-Backs in District 005 under the various Coalitions (millions $)

Coalition	District 005	District 025	Watermaster Section 10	CONAGUA
1,2	43.2	-5.8		-37.4
1,3	43.2		-2.9	-40.3
1,2,3	43.2	-5.8	-2.9	-34.5

Under the partial coalition of District 005 and District 025, {1, 2}, District 005 is compensated $43.3 million for the purchase of their water rights and reduces their overall demand. District 025 compensates District 005 $5.8 million and receives an increased minimum delivery. CONAGUA compensate District 005 $37.4 million to cover the remaining purchase price (Table 5-12).

Table 5-12 Demands, Deliveries, Values for Coalition {1, 2} Including Compensation from CONAGUA

Player	Category	Unit	Amount
District 005	Annual Demand	MCM/year	628
	Minimum Delivery	MCM/year	222
	Value of Delivery	$Million/year	19.1
	Value of Compensation	$Million/year	43.3
District 025	Annual Demand	MCM/year	1127
	Minimum Delivery	MCM/year	519
	Value of Delivery	$Million/year	44.6
	Value of Compensation	$Million/year	-5.8
CONAGUA	Value of Compensation	$Million/year	-37.4
Coalition Value		**$Million/year**	**101.2**

For the partial coalition, {1, 3}, between District 005 and Watermaster Section 10, District 005 sells their water rights for $43.3 million. Watermaster Section 10 compensates them for 6% of the water rights bought-back, or $2.9 million. Watermaster Section 10 only pays for the portion of District 005's water rights which could be delivered to them after the 1944 Treaty division and the large system losses. CONAGUA contributes $34.5 million to District 005 (Table 5-13).

Under the Grand Coalition, {1, 2, 3}, District 005 agrees to decrease their demand to 628 MCM/year for a total compensation of $43.3 million. District 025 and Watermaster Section 10 compensate District 005 for 18% of the water buy-backs, or $7.7 million. CONAGUA covers the remaining compensation of $34.5 million to District 005 (Table 5-14).

Table 5-13 Demands, Deliveries, Values for Coalition {1, 3} Including Compensation from CONAGUA

Player	Category	Unit	Amount
District 005	Annual Demand	MCM/year	628
	Minimum Delivery	MCM/year	222
	Value of Delivery	$Million/year	19.1
	Value of Compensation	$Million/year	43.3
Watermaster Section 10	Annual Demand	MCM/year	646
	Minimum Delivery	MCM/year	393
	Value of Delivery	$Million/year	33.8
	Value of Compensation	$Million/year	-2.9
CONAGUA	Value of Compensation	$Million/year	-34.5
Coalition Value		**$Million/year**	**93.2**

Table 5-14 Demands, Deliveries, and Values for the Grand Coalition {1, 2, 3} Including Compensation from CONAGUA

Player	Category	Unit	Amount
District 005	Annual Demand	MCM	628
	Minimum Delivery	MCM/year	222
	Value of Delivery	$Million/year	19.1
	Value of Compensation	$Million/year	43.3
District 025	Annual Demand	MCM/year	1127
	Minimum Delivery	MCM/year	519
	Value of Delivery	$Million/year	44.6
	Value of Compensation	$Million/year	-5.8
Watermaster Section 10	Annual Demand	$Million/year	646
	Minimum Delivery	MCM	393
	Value of Delivery	$Million/year	33.8
	Value of Compensation	$Million/year	-2.9
CONAGUA	Value of Compensation	$Million/year	-34.5
Coalition Value		$Million/year	**132.1**

Table 5-15 Characteristic Values of the Water Reduction Game Coalitions with inclusion of CONAGUA

Coalition	**Characteristic Value ($Million/year)**
$v(1)$	6.4
$v(2)$	34.4
$v(3)$	30.7
$v(1, 2)$	101.2
$v(1, 3)$	93.2
$v(2, 3)$	65.0
$v(1, 2, 3)$	132.1

From the characteristic values displayed in Table 5-15, the Core of the Water Demand Reduction game under the low flow analysis is defined by the bounds of allocations, **Ω_i**, to each player *i* as:

$$\Omega_1 \geq v(1) = 6.4$$

$$\Omega_1 \leq v(1,2,3) - v(2,3) = 67.1$$

$$\Omega_2 \geq v(2) = 34.4$$

$$\Omega_2 \leq v(1,2,3) - v(1,3) = 39.0$$

$$\Omega_3 \geq v(3) = 30.7$$

$$\Omega_3 \leq v(1,2,3) - v(1,2) = 30.9$$

The Water Demand Reduction game has 3 players who are dividing the benefits of cooperation. CONAGUA provides funding to District 005 under the various coalitions discussed in this section, but they do not receive a share of the coalition benefits and are therefore, not considered a player in the game. The Core of this game is shown on the simplex in Figure 5-6. The overall height of this simplex is equal to the Grand Coalition value, \$132.1 million.

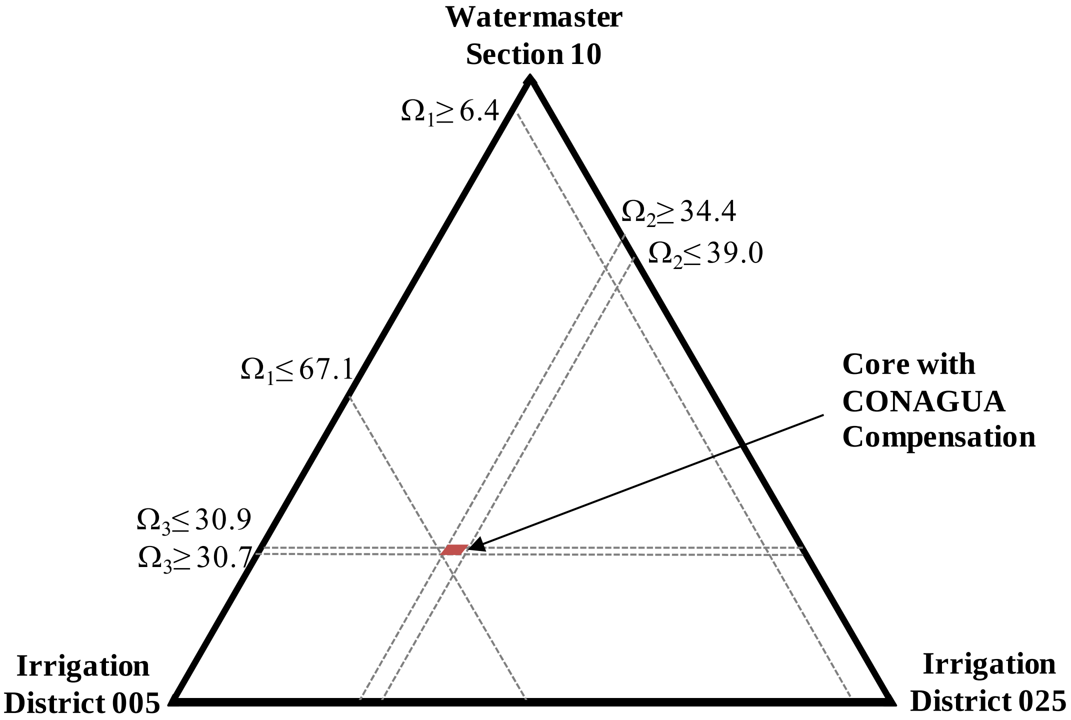

Figure 5-6 Core of the Water Reduction Game with the Inclusion of Compensation from CONAGUA

Under the compensation scheme presented in this section with the inclusion of compensation from CONAGUA, the size of the Core is reduced compared to the size of the simplex, or the value of the Grand Coalition. Most notably, the negotiation space for

Watermaster Section 10 varies by only \$0.2 million and District 025's varies by \$4.5 million. The Core is shifted towards District 005 indicating an increase in their allocation, while it has shifted away from District 025 and Watermaster 10 illustrating a decrease in their allocation. The Shapley allocation of this game does not fall inside the Core and does not satisfy the conditions of individual and group rationality and cannot be considered as an allocation. Since the Shapley allocation is not in the Core, the Nucleolus is used to select an allocation from the Core.

District 025 and Watermaster Section 10 have a decrease in their allocation under the compensation scheme with the inclusion of CONAGUA but still maintain an increase over their non-cooperative values (Figure 5-7). Watermaster Section 10's allocation is \$0.1 million above their non-cooperative allocation while District 025's is \$2.2 million above their non-cooperative allocation. District 005, however, has a substantial increase in their allocation with an additional \$42 million. The change in the allocations is strictly due to the increases in the coalition values that include District 005 and the compensation from CONAGUA (Table 5-16). The increase in District 005 coalitions correspond directly to the CONAGUA compensation values shown in the earlier Table 5-11.

District 005 provides most of the value to Grand Coalition under this scheme compared to the game without CONAGUA and therefore receives most of the value. Based on the cooperative analysis of the compensation scheme, District 005 would benefit the most; however, the downstream players receive a smaller allocation which is almost equal to their non-cooperative allocations. These results indicate that District 025 and Watermaster Section 10 may prefer the cooperative game without the inclusion of CONAGUA. The game theory calculations under this compensation scheme may not be the correct method for inclusion of an external funding source because it decreases the downstream players' power in the game.

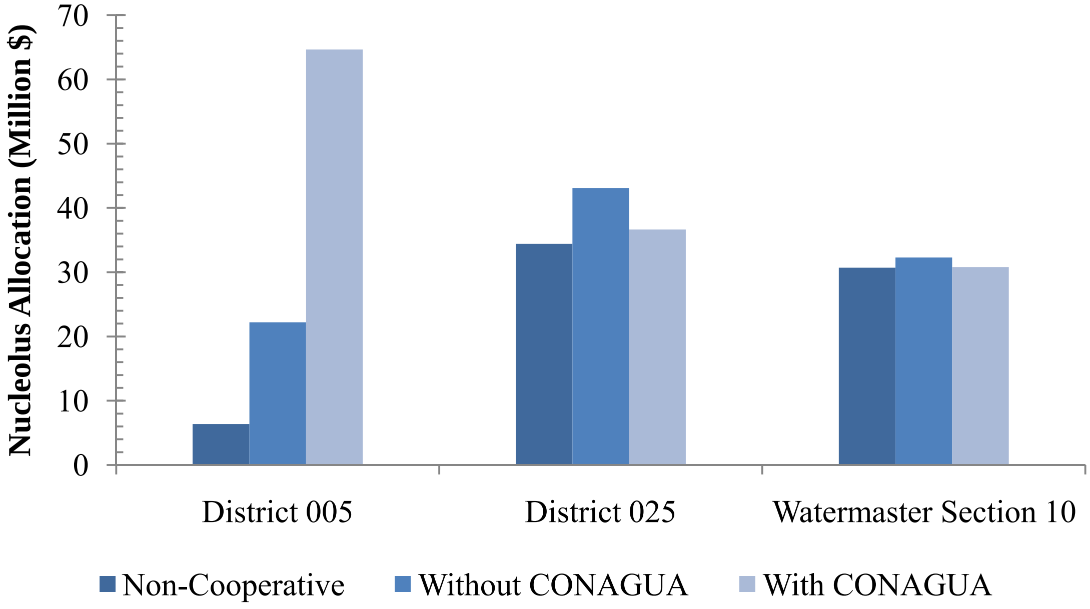

Figure 5-7 Comparison of the Non-Cooperative Allocations with the Nucleolus Allocations with and without Compensation from CONAGUA

Table 5-16 Change in Coalition Values with and without the Compensation from CONAGUA

Coalition	**Characteristic Value ($Million/year)**
$v(1)$	0
$v(2)$	0
$v(3)$	0
$v(1, 2)$	37.4
$v(1, 3)$	40.3
$v(2, 3)$	0
$v(1, 2, 3)$	34.5

5.3 Drought Analysis

An assumption was made in the Water Demand Reduction game that the demand remains constant throughout the simulation period, including drought periods. To determine the effects of drought on the game analysis, a period of historical drought in the basin was selected. The Record Drought in the Rio Grande/Bravo occurred from 1948 to1957 as shown in Figure 5-8 (Sandoval-Solis *et al.*, 2008). The cooperative game concepts are applied to the Record Drought. The Water Demand Reduction game is concerned with agricultural water deliveries, so to measure the effect of the water management scenario in critical periods of drought, the performance metrics of Vulnerability and Reliability are calculated for each player. The metric of Resilience does not apply for this analysis because it is dependent on the continuous annual flow sequence (See section 4.2.5). Resilience is a measure of a systems ability to recover from a deficit over time and in this analysis only the drought years are selected without the following non-drought years, so the recovery cannot be measured.

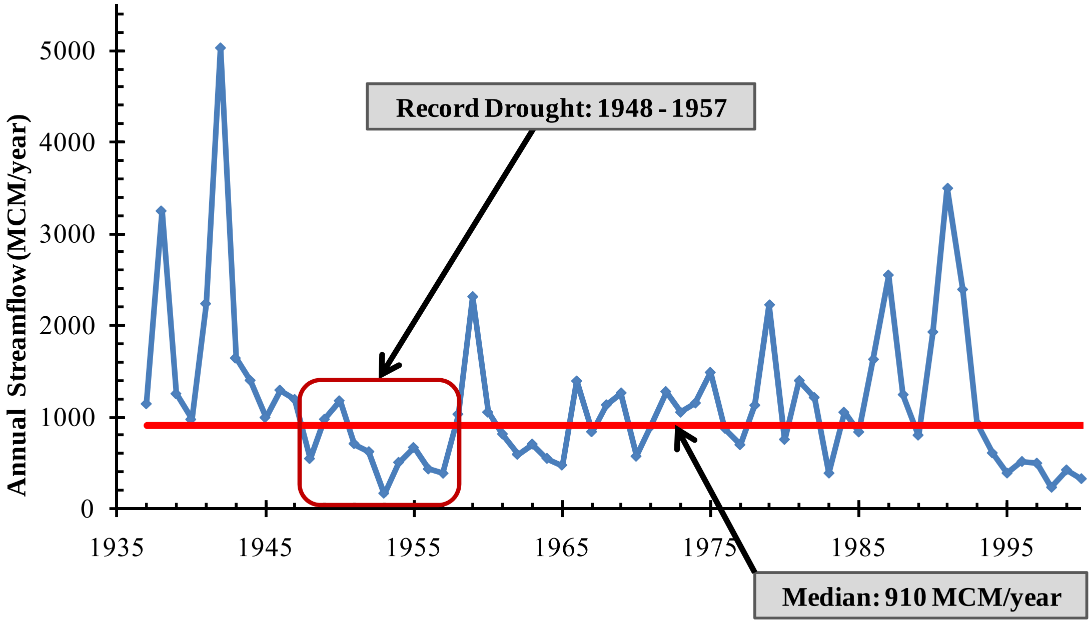

Figure 5-8 Periods of Drought in the Rio Grande/Bravo as shown in the Annual Streamflow Record at Fosters Ranch (Sandoval-Solis *et al.*, 2008).

The characteristic functions were calculated in the same manner described in Section 5.1.1. This analysis does not include the compensation described in Section 5.2. Under the non-cooperative coalitions, District 005 has a minimum delivery of 251 MCM, District 025 has a minimum delivery of 520 MCM and Watermaster Section 10 has a minimum delivery of 54.9 MCM (Table 5-17). Each non-cooperative coalition has an increased minimum delivery over the 60 year long-term analysis. Additionally, under this drought analysis, Watermaster Section 10's minimum delivery is 98% of their annual demand (Table 5-17).

Table 5-17 Demands, Deliveries, and Characteristic Values for Non-Cooperative Coalitions {1}, {2}, {3}

Player	Category	Unit	Amount
District 005	Annual Demand	MCM	1131
	Minimum Delivery	MCM/year	251
	Coalition Value	**$Million/year**	**21.6**
District 025	Annual Demand	MCM	1127
	Minimum Delivery	MCM/year	530
	Coalition Value	**$Million/year**	**45.6**
Watermaster Section 10	Annual Demand	MCM	647
	Minimum Delivery	MCM/year	638
	Coalition Value	**$Million/year**	**54.9**

District 005 and District 025 work cooperatively in the partial coalition {1, 2}. District 025 provides compensation to reduce District 005's annual water demand and in return, they receive an increased delivery (Table 5-18). Under this coalition, both players have an increased minimum delivery over the 60 year long-term analysis. Through cooperation under the Record Drought, District 005 and District 025 receive 100% of their annual demand for a coalition value, $v(1,2)$ = $151 million.

In the partial coalition {1, 3} Watermaster Section 10 funds water buy-backs in District 005 to reduce District 005's annual water demand (Table 5-19). Each player receives an increased water delivery compared to their non-cooperative values. Under this cooperative coalition, both players in this coalition receive 100% of their annual demand resulting in a coalition value of $v(1, 3)$ = $109.6

Table 5-18 Demands, Deliveries, and Values for Coalition {1, 2}

Player	**Category**	**Unit**	**Amount**
District 005	Annual Demand	MCM/year	628
	Minimum Delivery	MCM/year	628
	Value of Delivery	$Million/year	54.0
	Value of Compensation	$Million/year	43.3
District 025	Annual Demand	MCM/year	1127
	Minimum Delivery	MCM/year	1127
	Value of Delivery	$Million/year	96.9
	Value of Compensation	$Million/year	-43.3
Coalition Value		**$Million/year**	**151.0**

Table 5-19 Demands, Deliveries, Values for Coalition {1, 3}

Player	**Category**	**Unit**	**Amount**
District 005	Annual Demand	MCM	628
	Minimum Delivery	MCM/year	628
	Value of Delivery	$Million/year	54.0
	Value of Compensation	MCM	43.3
Watermaster Section 10	Annual Demand	$Million/year	646
	Minimum Delivery	MCM	646
	Value of Delivery	$Million/year	55.6
	Value of Compensation	$Million/year	-43.3
Coalition Value		$Million/year	**109.6**

The partial coalition {2, 3} cannot increase their benefit beyond the sum of their non-cooperative coalition values without the inclusion of District 005. The value of this partial coalition is $v(2,3)$ = $100.4 million. This partial coalition value is higher than the value in the 60 year long-term analysis because each player's minimum delivery is larger in the Record Drought period (Table 5-21). The coalition value is higher because the minimum delivery for these players occurs in the 1990's which is not included in the Record Drought period.

In the Grand Coalition {1, 2, 3}, all of the players in the game work cooperatively to increase their benefits beyond their individual coalition values. The downstream players, District 025 and Watermaster Section 10, fund the purchase of water rights in District 005 to reduce District 005's annual demand. In turn, each of the downstream players receives an increased water delivery. Under this coalition, each player has a minimum delivery equal to 100% of their annual demand (Table 5-20). The value of the Grand Coalition is $v(1, 2, 3)$ = $206.5.

The characteristic values for the 60 year long-term analysis and the Record Drought are calculated from the minimum delivery during that period to each player (Table 5-21). The non-cooperative coalition value for District 005, $v(1)$, is lower in the 60 year long-term analysis because the minimum delivery falls outside of the drought period under consideration (Table 5-21). The minimum delivery to District 005 occurs in 1958 when there is high flow in the basin. The minimum delivery to District 005 occurring outside the drought period is likely due to storage in the reservoirs being high enough to supply District 005's demand during the drought. As the drought progressed the storage levels likely fell to a level that could not support District 005's demand.

Table 5-20 Demands, Deliveries, and Values for the Grand Coalition {1, 2, 3}

Player	Category	Unit	Amount
District 005	Annual Demand	MCM	628
	Minimum Delivery	MCM/year	628
	Value of Delivery	\$Million/year	54.0
	Value of Compensation	\$Million/year	43.3
District 025	Annual Demand	MCM/year	1127
	Minimum Delivery	MCM/year	1127
	Value of Delivery	\$Million/year	96.9
	Value of Compensation	\$Million/year	-43.3
Watermaster Section 10	Annual Demand	\$Million/year	646
	Minimum Delivery	MCM	646
	Value of Delivery	\$Million/year	55.6
	Value of Compensation	\$Million/year	-43.3
Coalition Value		\$Million/year	**206.5**

Table 5-21 Characteristic Values for the 60 Year Long-Term Analysis and the Record Drought

Coalition	60 Year	Record Drought
$v(1)$	6.4	21.6
$v(2)$	34.4	45.6
$v(3)$	30.6	54.9
$v(1, 2)$	63.8	151.0
$v(1, 3)$	52.9	109.6
$v(2, 3)$	65.0	100.4
$v(1, 2, 3)$	97.6	206.5

The Core for the Record Drought is displayed on a simplex in Figure 5-9. The Core bounds for the Watermaster Section 10, under the Record Drought, have narrowed significantly, leaving their negotiation range at $0.7 million. The Core has also shifted towards District 005 and 025, increasing their upper bounds on negotiation, as well as, increasing their negotiation space. This increase is due to the size of the partial coalition of Districts 005 and 025 {1, 2} compared to the Grand Coalition {1, 2, 3}. Most of the $206.5 million of the Grand Coalition is negotiated for by these players because their partial coalition value, *v*(1,2), is 73% of the Grand Coalition value. Watermaster Section 10's non-cooperative value, *v*(3), increased by 18% while District 025's non-cooperative value, *v*(2), increased 39% and a District 005, *v*(1) had a significant increase of 65% (Table 5-21).

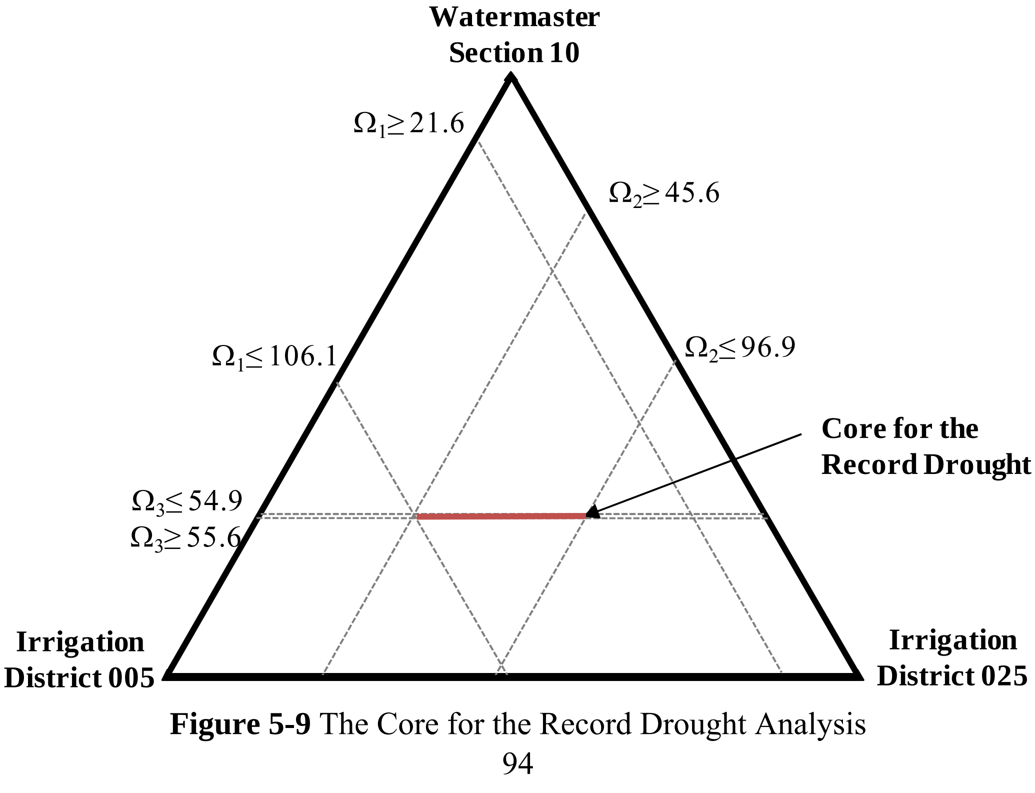

Figure 5-9 The Core for the Record Drought Analysis

From the Core an allocation may be selected utilizing one of the methods discussed in Section 3.3. For this analysis, the Shapley values are compared for the Grand Coalition allocations to all players in both the 60 year long-term analysis and the Record Drought (Figure 5-10). Under the Record Drought analysis all of the players receive a larger allocation than under the 60 year long-term analysis. This increase occurs because none of the players' minimum deliveries from the 60 year analysis occur in the Record Drought. The minimum deliveries for District 025 and Watermaster Section 10, under the 60year analysis, occur in the late 1990s. Since the minimum delivery values are higher for each player, the Shapely allocations are larger.

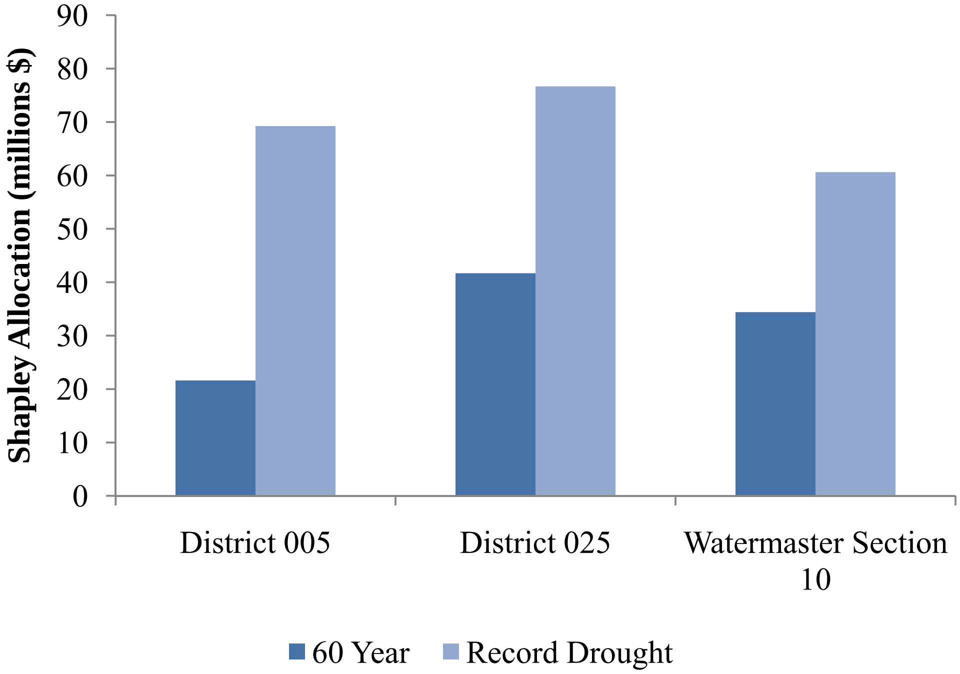

Figure 5-10 Comparison of the Shapley Values for Each Player in the 60 Year Long-Term Analysis and the Record Drought Analysis

The delivery measures under the Record Drought are not compared to the 60 year long-term analysis due to the disparate number years. To determine the effect of the drought analysis, the change from the non-cooperative coalitions to the Grand Coalition are evaluated. Each player would receive an increased allocation under the Record Drought, however, only District 005 would have significantly improved water deliveries as indicated by the change in their water delivery measures from the non-cooperative values to the Grand Coalition (Table 5-22). District 005 has a significant improvement of more than 30% in all delivery measures, including a78% change in minimum delivery and 70% increase in reliability (Table 5-22).

Under the Record Drought, Watermaster Section 10 has a notable change of 20% in Reliability and less than 1% change in the other measures (Table 5-22). If Watermaster Section 10 were to join this coalition, they would experience increased water delivery Reliability and but only a slight change under drought conditions. Watermaster Section 10 would only receive an increase in Reliability and allocation from the Grand Coalition under the Record Drought Conditions. In contrast, District 025 increases all of their performance measures with a 17% increase in their minimum delivery (Table 5-22). District 025 would receive an increase in all performance measures and an increased allocation from the Grand Coalition under the Record Drought analysis.

Table 5-22 Percent Change in Performance Measures for each Player between the Non-Cooperative Coalitions and Grand Coalition Under the Record Drought

Player	**Minimum Delivery (% Change)**	**Average Delivery (% Change)**	**Reliability (% Change)**	**Vulnerability (% Change)**
District 005	78	30	70	-41
District 025	17	5	10	-5
Watermaster Section 10	1	0	20	-1

5.4 Conclusions

This section described a cooperative game analysis of the Water Demand Reduction game. This analysis showed that each player received an increased allocation under the Grand Coalition. The Shapley Value and the Nucleolus were used to select an allocation of the cooperative gains. While these allocations yielded different results, an analysis of the propensity to disrupt showed that there each allocation was a reasonable starting point for negotiation.

In addition to the cooperative game analysis, a set of performance measures were calculated. The measures of Vulnerability, Reliability and Resilience demonstrated that under the cooperative solution, each player would receive a more dependable water supply. District 005 would receive the greatest improvement due to the decrease in their overall water demand while the downstream players receive a smaller increase. This small increase is due to the small amount of additional water these players would receive after accounting for the 1944 Treaty division and the large system losses as the water travels down the basin.

A second analysis evaluated the compensation scheme by inclusion of an outside funding source for the water buy-backs in District 005. The downstream players, District 025 and Watermaster Section 10, compensated District 005 only for the water they could receive after accounting for 1944 Treaty divisions and system losses. Results showed that under this compensation scheme, District 005 received the largest benefit of all players in the game. Due to District 005's large gains from the Grand Coalitions, the other players have reduced gains under this analysis and would not agree to join this coalition.

The last analysis presented in this section considered the Water Demand Reduction game under the Record Drought period of 1948 to 1957. The Record Drought analysis showed that each player would receive an increased allocation. This is largely due to the fact that the minimum deliveries for all users in this game fall outside of the Record Drought. Under the Record Drought analysis, Districts 005 and 025 would receive increased allocations from the Grand Coalition and improve water delivery under drought conditions. Although Watermaster Section 10 receives an increased allocation under this analysis, they only experience improved Reliability under the drought analysis.

6 CONCLUSIONS

This research is aimed at coupling cooperative game theory with a comprehensive water management model for a transboundary river basin. The objectives of this dissertation are to:

1. Construct and calibrate a water-planning model to represent the physical and institutional characteristics of a large scale, transboundary river basin (the Rio Grande/Bravo basin) with multiple players, jurisdictions, and water uses in multiple sectors;
2. Utilize the water-planning model to calculate values needed in the cooperative game theory calculations (characteristic function values);
3. Create river basin games where players cooperate and learn the benefits of that cooperation. The games in this research give players the opportunity to negotiate and divide the benefits of their cooperation;
4. Create a cooperative game theory framework that can be used to evaluate the benefits of cooperation in other transboundary river basins and in future water management scenarios in the case study basin; and
5. Utilize the Rio Grande/Bravo Basin as a case study for the dissertation objectives.

6.1 Discussion

Cooperative game theory was applied to the transboundary Rio Grande/Bravo basin as a study area. A comprehensive water planning model, described in detail in Section 4.1, was developed for the basin from the confluence of the Rio Conchos to the Gulf of Mexico, including the major tributaries in both the U.S. and Mexico. This model was constructed with the most comprehensive data set available for this basin. The model contains hydrologic and hydraulic information for period of 1940-2000 and includes over 135 surface water demand nodes representing more than 6,700 MCM/year of water demand. Twenty-five reservoirs with over 22 MCM of storage capacity are also included in the model. In addition to the physical attributes of the basin, the model contains logic for legal institutions in the basin including the two major water sharing agreements, the 1906 Convention and the 1944 Treaty, between the U.S. and Mexico.

Model calibration and testing demonstrates that the Rio Grande/Bravo water planning model captures the behavior of water management decisions in the basin. Historical water storage in the U.S. and Mexican accounts in the two bi-national reservoirs, La Amistad and Falcon, were compared to the modeled storage values. For the 15-year period of analysis, the difference between the historical and modeled storage is 3.6% for the Mexican accounts and 4.3% for the U.S. accounts.

A water management scenario was selected and evaluated as a cooperative game. The Water Demand Reduction game was developed with the players selected as the three largest individual agricultural water users in the basin; District 005, District 025 and

Watermaster Section 10. These players, located in both Mexico and the United States, were allocated the potential gains of cooperation rather than allocating the gains to the two countries as was done in previous transboundary river cooperative games.

The characteristic functions for the Water Demand Reduction game were calculated in monetary values using the Rio Grande/Bravo water planning model to determine the water delivery volumes. The characteristic functions were based on the minimum deliveries to a player over a certain period. The cooperative games were calculated for a 60-year, long-term period, a different compensation scheme which included outside funding and a record drought period to determine the effects of compensation changes and drought on the outcomes of the game.

In addition to the cooperative game analysis, performance measures were calculated for the water deliveries to each player. These performance measures were used to characterize the timing and reliability of the water deliveries to the players under the Water Demand Reduction game. In the Grand Coalition, District 005 received the highest increase in performance. This delivery improvement is due to the decreased water demand, which no longer overtaxes the system.

Under the Grand Coalition, District 025 and Watermaster Section 10 experience small increases in their water delivery performance. The largest benefit to District 025 is an increase in both the Reliability and Resilience of their deliveries. The small changes in water delivery performance are related to the small volumes of additional water available to each downstream player. The downstream players received small volumes of additional water because of the 1944 Treaty and system losses. The 1944 Treaty divides any water from the Rio Conchos with 1/3 to the U.S. and 2/3 to Mexico. Additionally, any water from the Rio Conchos has an 80% system loss before reaching the lower basin. These losses create small deliveries to the downstream players, particularly Watermaster Section 10, who receives only 1/3 of water from the Rio Conchos.

The characteristic functions of the game were calculated based on the minimum annual delivery to each player. A monetary value of these minimum deliveries was determined based on agricultural production. From the characteristic functions, a Core of the game was determined. The Core demonstrated the effects of the small increases in water to the downstream players, especially Watermaster Section 10, with their narrow negotiation ranges which can be attributed to their small deliveries after the division under the 1944 Treaty and the 80% system losses. From the Core, the Shapley and Nucleolus allocation methods were applied to select unique allocations from the Core. Utilizing the concept of the propensity to disrupt, the stability of each of these allocations were calculated and the analysis demonstrated that they provided similar results.

Under both the Shapley and the Nucleolus, District 005 receives the largest increase in benefits. This is largely due to the fact that a game does not exist without the inclusion of District 005. However, without the inclusion of the downstream players District 005 does not have an opportunity to improve their allocation, so there is incentive to share the gains with the downstream players.

Further analysis revealed that including CONAGUA in the compensation scheme in the Water Demand Reduction game was not an appropriate method. The compensation to District 005 outweighed the benefits to District 025 and Watermaster Section 10, who had larger monetary benefits under their non-cooperative coalitions than in the Grand Coalition. Also, the changes in performance measures to District 025 and Watermaster Section 10 were not large enough to overcome their decreased allocation under the compensation scheme. There was no indication that either downstream player would cooperate under the compensation scheme.

The final analysis compared the cooperative game outcomes of a Record Drought (1948-1957) analysis to the 60-year, long-term analysis. Under the drought analysis, the allocations to each player were increased with the Shapley Allocation from the Grand Coalition. These allocations were higher than under the 60 year analysis because the minimum deliveries under the 60 year analysis are not captured in the Record Drought. The increase in minimum deliveries increases the value of the Grand Coalition and in turn, the allocations to each player. Under this analysis, Watermaster Section 10 could agree to join the Grand Coalition.

In all three analyses, District 005 receives the greatest increase in benefit through cooperation. Their large increase in allocated benefit occurs because a game does not occur without District005. The two lower basin players have an increased benefit, but without an option to form a partial coalition without District 005, they cannot increase their allocations. It is important to note that without the inclusion of the downstream players, there is also not a game. Due to this characteristic, District 005 has incentive to share coalition benefits with the downstream players.

6.2 Conclusions

This dissertation met the objectives outlined in the Introduction and described in Section 6.1 as follows:

1. A water management planning model was constructed and calibrated for a large scale, transboundary river basin utilizing the Rio Grande/Bravo basin as a case study. This planning model included over 155 water demand sites, 25 storage reservoirs and logic for water policies related to bi-national water sharing agreements. Testing and calibration of storage values in the two international reservoirs shows that the water planning model is a reasonable representation of water management in the Rio Grande/Bravo basin.
2. The water planning model was used to calculate the minimum delivery to each player, in each coalition in the game which was set at the characteristic value for each coalition.
3. The Water Demand Reduction Game allowed players to cooperate to fund water buy-backs in the District 005. From the characteristic functions, the Core of the game was calculated to determine the bounds of negotiation for each player.

4. The analysis presented in this dissertation allows for the creation of transboundary river basin games where players cooperate and learn the benefits of that cooperation. The games in this research give players the opportunity to negotiate and divide the benefits of their cooperation as demonstrated with the determination of the Core;
5. The methods utilized in this dissertation can be applied to any transboundary river basin to for any management scenario determine if cooperation provides additional benefits to each player. For the case study basin, the Rio Grande/Bravo, these same concepts can be applied to any player and an; and
6. Each of the objectives has been applied to the Rio Grande/Bravo Basin as a case study.

Cooperative game theory can be applied to transboundary river basins to measure the additional benefits from cooperation. Cooperative game theory also provides tools to equitably allocate the potential gains of cooperation of the coalition to the individual players in that coalition. Cooperative game theory has also been applied to the Syr Darya in Central Asia (see Appendix) allocating cooperative benefits to the individual countries as the players demonstrating that each country benefits through participation in the new treaty. The cooperative game theory is flexible in player definition in transboundary river basins.

This research has shown that cooperative game theory can be a useful tool for evaluating the water management scenarios in the Rio Grande/Bravo basin in conjunction with the Rio Grande/Bravo water planning model. The water planning model is a reasonable representation of water management in the basin for both the U.S. and Mexico and allows the cooperative game analysis to be applied to individual players in the basin. The water planning model is created from a comprehensive database of the Rio Grande/Bravo and additional data in the model would likely not improve the results of the cooperative game analysis.

Increased minimum water deliveries provide additional benefits to the players in the Water Demand Reduction Game. However, relatively small water volumes are available to District 025 and Watermaster 10 after the water rights buy-backs in District 005. These small volumes are due to the large system losses (80%) and the 1944 Treaty division of water from the Rio Conchos reaching the Rio Grande/Bravo. This restriction is especially clear with Watermaster 10 with their small increases in performance measures, as well as, their narrow negotiation range in the Core.

The selected water management scenario used in this analysis does not indicate that there is enough benefit provided to each player to cooperate. The lower basin players, who would fund the water rights buy-backs in District 005, do not receive sufficient benefit from their water deliveries to offset the cost associated with the buy-backs, especially when considering the additional compensation scheme with the inclusion of CONAGUA. However, under the Record Drought analysis presented in this dissertation, the downstream players may agree to implement the scenario based on their increased allocations.

6.3 Recommendations

This dissertation has shown that cooperative game theory can be a useful tool for determining increased benefits from cooperation and allocating those benefits to individuals in a game and it has also been shown as effective tool in allocating the gains to countries as in the case of the Syr Darya. The Rio Grande/Bravo game selected for this research does not provide enough benefit to some of the players to implement this scenario. Additional research is needed related to the economic values used in this cooperative game application. Each player may value their water at different rates which could affect the outcomes of the game. Additionally, the compensation scheme needs to be evaluated to determine what value District 005 would accept to retire their water rights. This application assumed that District 005 would require the same value for delivery and each million cubic meter of bought back water right. Further analysis is needed to determine a realistic value for water buy-backs.

Additional research is required for the drought analysis. While the drought analysis in this dissertation has shown increased benefits to players in the Water Demand Reduction game, this drought analysis may not be an appropriate measure of drought. The minimum delivery in District 005 occurs in a different decade than the minimum deliveries in the lower basin. This demonstrates that due to the large size of the Rio Grande/Bravo basin, a large deficit period in one part of the basin may not correspond to a large deficit period in another part of the basin. As scenarios for climate change are developed and implemented in the Rio Grande/Bravo planning model, they should be evaluated under the cooperative game analysis to determine their effects on the cooperative results. Using climate change scenarios may demonstrate the importance of this type of planning for drought conditions.

The game theory analysis needs to be applied water management scenarios which produce a larger benefit to the lower basin players. The lower basin players need a large delivery to offset the losses in the basin and other scenarios need to be evaluated. Currently, more water management scenarios are being developed for the Rio Grande/Bravo basin. These scenarios, especially the ones which implement management changes in the lower basin, should be evaluated under the cooperative game concepts to demonstrate the added value through cooperation to the players. Allowing the lower basin players to cooperate without the inclusion of District 005, may give them more power in the negotiation and increase their allocations form the cooperative benefits.

As new water management scenarios are developed, analysis with other players can be conducted. The players in a game are not restricted to the three selected in this dissertation. The flexibility of selecting players has been demonstrated in this dissertation and in the Syr Darya game (see Appendix). Players in the games could be municipalities in addition to agricultural users, particularly when exploring the transfer of water supplies between the two users. Another player could be the environment if environmental flows are considered in future scenarios. This framework is flexible enough to consider other players in future analyses.

In addition to the cooperative game analysis, a set of performance measures for water deliveries were calculated. The cooperative game analysis allocated the monetary benefits from the cooperation, but does not demonstrate the additional benefits a player could receive through cooperation. The performance measures highlight the change in water delivery to each player and can be used by the players to determine if their additional benefit. The measure of Reliability, or the probability of a deficit not occurring in a period, is important to report to show the improvement in deliveries to a player. These performance measures could also be used to calculate the performance metric. In this dissertation, minimum delivery was selected, but other performance metrics could be used.

APPENDIX

Cooperative Game Theory for Transboundary River Basins: The Syr Darya Basin

Calculating the Benefits of Transboundary River Basin Cooperation: The Syr Darya Basin

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INTRODUCTION

River basin management is as varied as each basin under consideration. Rapidly increasing populations and economic development in many basins often place additional demands on limited water supplies. Transboundary river basins are basins which border two or more countries and add complexity to water management issues. There are over 200 transboundary river basins around the world (Wolf, 2002). Water planning in these basins is often difficult because they are subject to the politics, laws and regulations of all the countries in those basins.

Historically, riparian nations have shared transboundary river basins through treaties and agreements. Wolf (2002) has identified over 400 such agreements signed since 1870. The Syr Darya basin, located in Central Asia, is a transboundary river shared by four countries (Kyrgyzstan, Uzbekistan, Tajikistan, and Kazakhstan). The Syr Darya riparian countries have existing water sharing agreements and they are currently negotiating a new water agreement (ADB, 2007). In this paper, we use cooperative game theory coupled with a water planning model to quantify the benefits of cooperation to the Syr Darya riparian countries under this new water and energy sharing agreement.

The Syr Darya originates in the mountains of Kyrgyzstan, and flows through Tajikistan, Uzbekistan and Kazakhstan before draining into the Aral Sea (Figure 1). The Syr Darya presents unique transboundary water management challenges, because prior to 1991 it was part of the Soviet Union and was managed by a single, central government that emphasized large-scale cotton production in the basin resulting in a large demand for growing period irrigation water (Weithal, 2002). The 14-billion m^3 active storage Toktogul reservoir was built in the Kyrgyz mountains to provide water storage for the large downstream irrigation demands. Additional information about the Syr Darya basin and Central Asia can be found in Weinthal (2002), Antipova et al., (2002) McKinney (2003), and Micklin (2005).

Following the breakup of the Soviet Union in the early 1990s, the Syr Darya became a transboundary river basin flowing through four countries rather than one, and the management of the river became much more difficult since each country attempted to maximize their benefits from the river, often at the expense of the other countries. Kyrgyzstan wanted to use the Toktogul and adjacent downstream cascade of reservoirs to generate wintertime hydropower, and Uzbekistan and Kazakhstan wanted to use the water for summertime irrigation. To reconcile the resulting competition for water between the newly independent nations, an agreement “On Cooperation in the Field of Joint Management and Conservation of Interstate Water Resources” was signed in 1992 (Almaty agreement). The Almaty agreement created the Interstate Commission for Water Cooperation (ICWC) and associated river basin organizations for the Syr Darya and Amu Darya and confirmed the previous Soviet water allocation levels for each country (ICWC, 1992). Due to several factors over the ensuing years, including the transition to market-based pricing for fuels and other resources and a struggling economy, Kyrgyzstan increased winter releases from Toktogul reservoir for hydropower generation, leading to irrigation water deficits in the downstream countries.

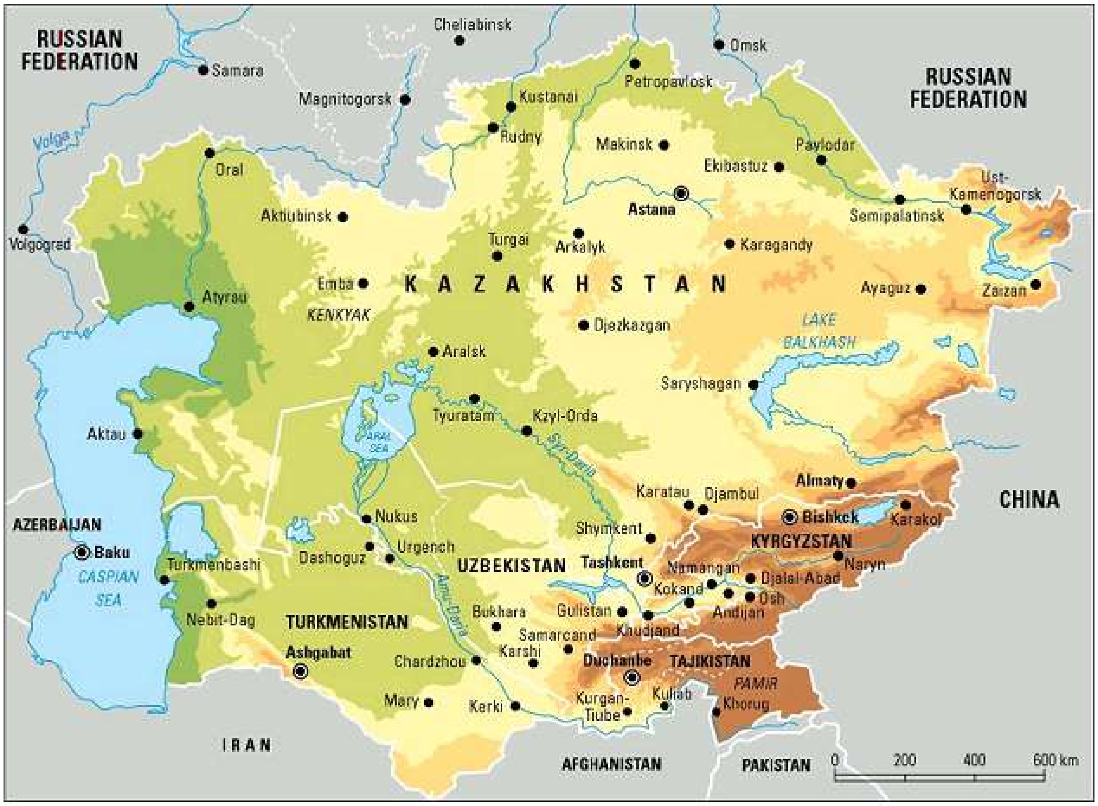

Figure 1. Map of the Aral Sea basin showing the Syr Darya and Amu Darya (Source: The World Bank design by Philippe Rekacewicz, UNEP/GRID-Arendal http://go.worldbank.org/A7M424G5Z0)

To alleviate the developing water sharing problems in the basin, the riparian nations signed the “Agreement on the Use of Water and Energy Resources of the Syr Darya Basin” in 1998 (1998 Agreement) that outlined a power and water sharing agreement among the countries (ICWC, 1998). The 1998 agreement called for negotiating an annual water release schedule for Toktogul reservoir, the delivery to Uzbekistan and Kazakhstan of surplus electricity generated as a result of the releases, and fuel deliveries from Uzbekistan and Kazakhstan to compensate for foregone

Since the establishment of the 1998 Agreement, in some years (typically wet years), energy deliveries to Kyrgyzstan from the downstream countries have been less than needed for Kyrgyz wintertime energy needs. In these years, Kyrgyzstan has increased winter releases from Toktogul to make up this energy deficit. This has exposed difficulties in the 1998 Agreement: (1) multi-year hydrologic fluctuations are not taken into account; and (2) reservoir storage services are not valued. The Syr Darya riparian countries are revising the Agreement to address these difficulties (ADB, 2007). The revised Agreement follows a similar water and power sharing framework as the 1998 Agreement, but adds consideration of storage (not just releases, see Table 1) in Toktogul reservoir and hydropower production and transfer from Tajikistan’s midstream Kayrakum reservoir.

Table 1. Proposed Revision of the Schedule of Water Releases From Toktogul Reservoir (Source: ADB 2006)

Water Availability	Inflow (billion m^3)	Release (billion m^3)		Change in Storage (billion m^3)	
		Vegetation period[1]	Non-vegetation period[2]	Drawdown	Impoundment
Average	11.9	5.0	6.5		0.4
Low	8.9	6.2	6.0	3.3	
High	14.9	4.0	7.0		3.9

1. Vegetation period = April to September
2. Non-vegetation period = October to March

Conflict over water use in the Syr Darya basin highlights the need for cooperation among the riparian countries. Many transboundary river basin conflicts arise over due to asymmetries in access to data, wealth, or even location in a basin. Locational asymmetry (i.e. upstream-downstream location) allows Kyrgyzstan, which owns and operates the basin's major storage reservoir, to have strategic influence over the other countries in the Syr Darya basin, albeit, at the cost of angering the downstream countries because of flooding and irrigation water deficits. So, while Kyrgyzstan may find itself in a position of some independence, it is also in a position to benefit from cooperation. Cooperative game theory provides a means of computing the benefits of cooperation and the equitable allocation of cooperative gains to the riparian countries (Just and Netanyahu, 1998).

Cooperative game theory has been applied in several areas of water resources management. One of the first was presented by Rogers (1969) for the Ganges and Brahmaputra rivers where he demonstrated that game theory can provide a basis for treaty negotiation between Pakistan and India for their shared water resources. Game theory has also been applied in the areas of cost allocation for water development projects (Suki and Nakayama, 1976; Straffin and Heaney, 1981), regional wastewater treatment (Giglio and Wrightington, 1972; Heaney and Dickinson, 1982; Loehman *et al*., 1979; Dinar *et al*. 1986; Dinar and Yaron, 1986), water quality (Kilgour *et al*., 1988; Dinar and Howitt, 1997), and transboundary water resources management (Becker and Easter, 1997; Becker and Easter, 1998). While this list represents application to a wide range of water resources problems, limited work has been reported on applying cooperative game theory to transboundary river basins.

In the area of transboundary river basins, cooperative game theory has been applied to the Ganges-Brahmaputra (Rogers, 1969; Rogers, 1993), the Nile (Wu, 2000; Wu and Whittington, 2006), and the Tigris-Euphrates (Kucukmehmetoglu, 2002; Kucukmehmetoglu and Guldmann, 2004). Additionally, cooperative game theory has been applied for water trading from the Nile among the Middle East countries of Egypt and Israel, and with the regions of the Gaza Strip and the West Bank (Dinar and Wolf, 1994). These works have shown that cooperative game theory can be used to quantify the benefits of cooperation among riparian countries.

In this paper, we use cooperative game theory to quantify the benefits of cooperation under water sharing agreements in the transboundary Syr Darya basin. Water-sharing agreements can be developed in a non-cooperative setting, where each country attempts to maximize its own returns through independent actions, often at the expense of other riparian users. This would be the case in the Syr Darya if Kyrgyzstan were to choose to generate all of its wintertime energy needs through hydropower releases from Toktogul reservoir. However, in a cooperative negotiation framework, countries work together to maximize their collective benefits and seek gains beyond what they could get if they act individually. This has been the motivating factor behind the existing Syr Darya Agreement and its proposed revisions.

Previously, cooperative game theory methods have not been applied to the Syr Darya, however other forms of game theory have been used to study water sharing in the basin. Non-cooperative game theory methods have been applied to evaluate water sharing agreements among the riparian countries in the Aral Sea basin. These include interconnected games in the Amu Darya (Bennett *et al*., 1998), experimental games in the Syr Darya (Abbink et al., 2005), and a graph model for conflict resolution in the Syr Darya (Nandalal and Hipel, 2007). Bennett *et al.* (1998) applied interconnected games, a class of non-cooperative games where players in a weak position try to improve their position by linking to other issues, to the Aral Sea basin by linking air pollution remediation to water diversions for Tajikistan and Uzbekistan. Abbink et al. (2005) coupled a water resources planning model with experimental game theory to study the likelihood of water management cooperation in the Syr Darya. Experimental game theory was used to determine the effect of new reservoirs in Uzbekistan on the economies of the basin states. The authors' analyses demonstrated that to maximize the benefits, cooperation must exist. Nandalal and Hipel (2007) utilized a graph model for conflict resolution to evaluate the stability of water decisions among countries in the Syr Darya basin and showed that the 1992 Almaty Agreement was the most stable decision of the ones they considered.

This paper uses cooperative game theory to examine the potential benefits to the riparian countries of the proposed revisions to the 1998 Syr Darya Agreement. Cooperative game theory is used to quantify the value of cooperation for the participating countries. Further, cooperative game theory provides ways to determine equitable allocations of the benefits of cooperation to the participating stakeholders as well as determining the likely satisfaction of countries regarding their allocation or their willingness to cooperate.

COOPERATIVE GAME THEORY IN THE SYR DARYA BASIN

In the Syr Darya basin with its four riparian countries -- Kyrgyzstan (Kg), Tajikistan (Tj), Uzbekistan (Uz) and Kazakhstan (Kz) -- a total of 15 coalitions or partnerships of the countries are possible (see Table 2). The coalitions can range from individual countries acting alone (non-cooperation) to all countries cooperating (the Grand Coalition). Partial coalitions are also possible. The proposed revision to the 1998 Agreement has allocations of the Syr Darya flow to each country as fixed percentages according to the 1992 Almaty Agreement (ICWC, 1992); Kyrgyzstan can divert 0.5% of the water, Tajikistan 7%, Uzbekistan 50.5%, and the remaining 42% is for Kazakhstan. The coalitions described in the following sections assume that if a coalition forms, the countries will work together even without the cooperation of the other countries not in the coalition. Additionally, each country's diversion is limited to the percentages described above regardless of whether a country is participating in a coalition, and the coalitions cannot restrict the diversions of non-participating countries.

Table 2. Coalitions in the Syr Darya Game

Coalition Type	**Coalitions Members**
1 country coalitions	{Kg}, {Tj}, {Uz}, {Kz}
2 country coalitions	{Kg, Tj}, {Kg, Uz}, {Kg, Kz}, {Tj, Uz}, {Tj, Kz}, {Uz, Kz}
3 country coalitions	{Kg, Tj, Uz}, {Kg, Tj, Kz}, {Kg, Uz, Kz}, {Tj, Uz, Kz}
4 country coalition	{Kg, Tj, Uz, Kz}

Single Country (Independent) Coalitions

When there is no cooperation, each country tends to act independently to maximize their individual benefits from water use. Starting upstream, we can consider that when Kyrgyzstan acts independently it releases sufficient water to generate enough electricity to cover its internal energy demands (their agricultural water needs, diverted downstream of the dam, are also covered by these releases); however, there is no consideration of the irrigation water needs of the downstream countries. The independent Kyrgyz "power" releases occur to generate wintertime hydropower. Moving downstream (Figure 1), Uzbekistan receives a portion of the power releases, then Tajikistan receives their share; after that, Uzbekistan receives the remainder of their share plus agricultural return flows from Tajikistan. Finally, Kazakhstan receives their share plus the return flows from Uzbekistan. Tajikistan, Uzbekistan and Kazakhstan all use their shares of the water for irrigated agriculture.

Two Country Coalitions

According to the existing agreements, Kyrgyzstan and Tajikistan control at most 7.5% of the water in the basin. They do not have sufficient influence or resources to benefit from forming a coalition and the Kyrgyzstan-Tajikistan coalition {Kg, Tj} has the same benefit as the sum of the single country results.

A Kyrgyz-Uzbek coalition {Kg, Uz} could result in increased benefits over the independent case. Under this coalition, Kyrgyzstan would release sufficient water to maximize Uzbekistan's benefits from agricultural use of the water (subject to Uzbekistan's diversion limit in the basin, 50.5%). Tajikistan and Kazakhstan may divert their shares of the releases; however, their benefits are not included in the calculations for this coalition. Surplus electricity (in excess of Kyrgyzstan's domestic demand) generated as a result of the release to Uzbekistan, is delivered to Uzbekistan and sold in an energy market (while not existing at this time, there are plans for an active electricity market in the Central Asian region in the future). As a result of managing the basin for Uzbekistan's summertime irrigation needs, Kyrgyzstan may experience a wintertime energy deficit, which is compensated for by cash payments or an equivalently valued fuel supplement from Uzbekistan.

Considering a Kyrgyz-Kazakh coalition {Kg, Kz}, Kyrgyzstan would release sufficient water to maximize Kazakhstan's benefits from agricultural use of the water (again subject to diversion limits in the basin). Tajikistan and Uzbekistan may still draw their share of the releases but their benefits are not included in the calculations for this coalition. Surplus electricity generated as a result of these releases is delivered to Kazakhstan and sold in an energy market and any Kyrgyz wintertime energy deficit is compensated by Kazakhstan.

In a Tajik-Uzbek coalition {Tj, Uz}, Kyrgyzstan acts independently, releasing sufficient water to cover its internal energy needs; however, there is no consideration of the downstream need for irrigation water. Tajikistan receives 7% of the power releases and uses this water to maximize their benefits from agricultural production. Uzbekistan receives 50.5% of the Kyrgyz releases plus return flows from Tajikistan and uses this water to maximize agricultural benefits. Kazakhstan is still allowed to divert their share of the water, but their benefit is not included in the coalition value. Surplus energy generated by Tajikistan (due to releases from the Kayrakum reservoir) is transferred to Uzbekistan who sells this power on the market. This model assumes that Uzbekistan and Tajikistan equally share the profits from the power sale.

Considering a Tajik-Kazakh coalition {Tj, Kz}, they do not have sufficient influence or resources to benefit from forming a coalition, and the coalition value is the sum of the independent country results.

The Uzbek-Kazakh {Uz, Kz} coalition of the major water users in the basin is very important. In this coalition, Kyrgyzstan releases sufficient water to cover its internal energy demands and its 0.5% of the water. Tajikistan receives 7% of the releases and uses this water for agricultural production. Uzbekistan receives 50.5% of the releases and Tajik return flows and uses this water for agricultural production. Kazakhstan receives 42% of the releases plus Uzbek return flows and uses this water for agricultural production.

Three-Country Coalitions

Under a Kyrgyz-Tajik-Uzbek {Kg, Tj, Uz} coalition, Kyrgyzstan would release sufficient water to cover the Uzbek and Tajik irrigation demands. Any Kyrgyz energy deficit is made up for by a fuel supplement from Uzbekistan. Uzbekistan receives the (optimal) water from these releases and uses this water for agricultural production. Surplus Kyrgyz energy is sent to Uzbekistan who sells it on the market. Tajikistan receives no more than 7% of the releases, and surplus hydropower generated by Tajikistan is transferred to Uzbekistan who sells it on the market and shares the profits with Tajikistan. Kazakhstan may divert their share of the water, but there is no power sharing with Kazakhstan and their benefit is not included in the coalition value.

The draft agreement does not outline a power sharing agreement for the {Kg, Tj, Kz} coalition, indicating the difficulty in forming this coalition. For our purposes, we take the value of this coalition to be the sum of the non-cooperative values.

Under a Kyrgyz-Uzbek-Kazakh {Kg, Uz, Kz} coalition Kyrgyzstan releases sufficient water to cover both the Uzbek and Kazakh irrigation demands (subject to the basin diversion limits), and Kyrgyz energy deficits are compensated for by cash or fuel supplements from Uzbekistan and Kazakhstan. Tajikistan can still divert their 7% but there is no power sharing agreement with Tajikistan in this coalition and their benefits are not included in the coalition value.

Under a Tajik-Uzbek-Kazakh {Tj, Uz, Kz} coalition, Kyrgyzstan releases sufficient water to produce hydropower to cover its power demand and the downstream countries maximize their agricultural production with their share of the power releases. Additionally, Tajik hydropower is sent to Uzbekistan who sells it on the market and splits the profits with Tajikistan.

Four Country (Grand) Coalition

In the “Grand” Kyrgyz-Tajik-Uzbek–Kazakh {Kg, Tj, Uz, Kz} coalition Kyrgyzstan releases sufficient water to cover the irrigation demands of all three downstream countries (still observing basin diversion limits). Surplus Kyrgyz hydropower is split between Uzbekistan and Kazakhstan in proportion to the water that they receive. Kyrgyz energy deficits are compensated by fuel supplements from Uzbekistan and Kazakhstan in proportion to their profits from selling the energy surplus. Surplus Tajik hydropower is sent to Uzbekistan who sells it on the market and splits the profits with Tajikistan.

SYR DARYA RIVER BASIN OPTIMIZATION MODEL

A river basin model is used to calculate the values (benefits of cooperation) of the coalitions discussed in the previous section. The model, programmed in GAMS (Brooks *et al.*, 2006), includes hydropower generation and agricultural production as the two largest uses of Syr Darya water. The model neglects other uses such as municipal demands in all countries, which are small relative to agricultural water use. The model is similar in extent to the Syr Darya models of Keith and McKinney (1997), GEF (2002), and Antipova et al. (2002) in which the main tributary flows are allocated to aggregate downstream water demands for beneficial use, but the level of detail is at the country level, or at most irrigation district level.

The model allocates water for energy and agricultural production for one year with a monthly time step. A schematic of the river network used in the model is shown in Figure 2. Kyrgyzstan owns and operates a cascade of 5 reservoirs (Toktogul, Kurpsai, Tashkumyr, Shamaldysai and Uch-Kurgan) with hydropower plants located in the lower reaches of the Naryn River. The total rated capacity of the Naryn Cascade is 2,870 MW and the average long-term output of electric power is 10,000 million kWh/year (Antipova et al., 2002). Hydropower accounts for over 90% of the electric power generation in Kyrgyzstan, with over 97% of the capacity concentrated in the Naryn Cascade controlled by Toktogul Reservoir (1200 MW). The other reservoirs of the cascade have small storage capacity and provide daily or weekly control of discharges from Toktogul. Basic characteristics and parameters of the Naryn Cascade are given in Antipova et al. (2002).

Further downstream in the Syr Darya basin, Tajikistan owns and operates Kayrakum reservoir as a daily and seasonal reregulation reservoir with an active capacity of 2.6 km^3 and an installed power generating capacity of 126 MW. Tajikistan draws irrigation water directly from the reservoir. Various characteristics of the Syr Darya reservoirs are shown in Table 3 (McKinney and Kenshimov, 2000).

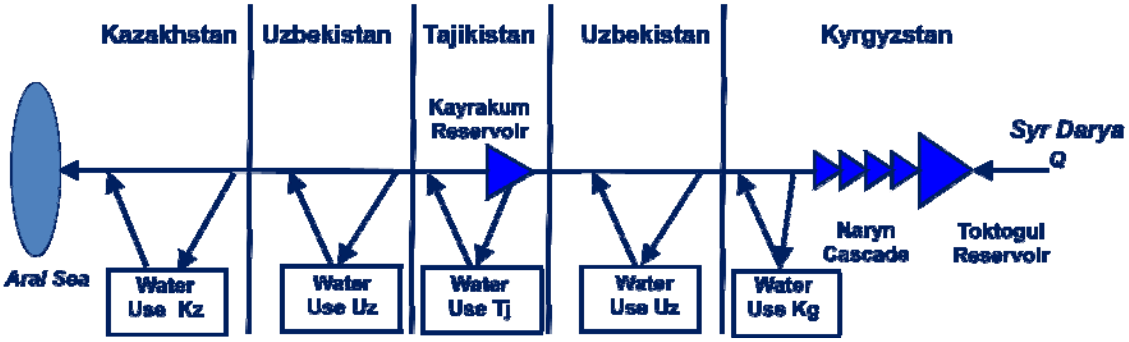

Figure 2. Syr Darya Basin Water Use Schematic**.**

The Draft agreement deals specifically with water from the Naryn River and neglects water from other tributaries (ADB, 2007). The Naryn River in Kyrgyzstan is a glacier fed river with a fairly large and constant annual baseflow of about 6 billion m^3 per year. The Draft Agreement notes that the average annual inflow to Toktogul reservoir on the Naryn River is 11,900 million m^3 (8,900 and 14,900 million m^3 for dry and wet years, respectively). Additionally, the Draft agreement specifies a flow into the Northern Aral Sea of 5,000 million m^3 per year.

In the model, Kyrgyzstan's energy demand (11,220 million kWh per year (McKinney and Kenshimov, 2000)) is satisfied by hydropower generated from releases from Toktogul reservoir and the Naryn cascade. If the Kyrgyz energy demand cannot be met through hydropower production then energy is purchased to cover the deficit at a cost of $0.08 per kWh. The operation and maintenance cost of the hydropower facilities is estimated to be $0.01 per kWh (Huchens, 1999).

The model includes irrigated areas in each country (Table 4). A number of different crops can be grown in each country including cotton, winter wheat, rice, fruit and vegetables. In the model, the crops are aggregated into a single crop for each country with a single annual water demand and profit per hectare as shown in Table 4, derived from Keith and McKinney (1997), who analyzed farm level data from a number of previous studies in the basin for the negotiation of the 1998 Agreement. Irrigation return flows from Tajikistan, Uzbekistan and Kazakhstan are assumed to be 40% of the diversion.

Table 3. Characteristics of the Syr Darya Reservoirs (Source: McKinney and Kenshimov, 2000).

Item	**Toktogul**	**Kurpsai**	**Tashkumyr**	**Shamaldysai**	**Uchkurgan**	**Kayrakum**
Power capacity (MW)	1,200	800	450	240	180	126
Total storage (million m^3)	19,500	370	140	39.4	52.5	3,400
Active storage (million m^3)	14,000	35	10	5.42	20.9	2,550
Hydropower unit efficiency (%)	87	90	85	80	80	86

Table 4. Irrigated Crop Characteristics (Source: Keith and McKinney (1997) and GEF (2002)).

Country	**Profit ($/ha)**	**Maximum Available Area (ha)**	**Annual Water Requirement (m^3/ha)**
Kyrgyzstan	169.2	456,000	12,645
Tajikistan	432.0	262,000	12,734
Uzbekistan	448.7	1,892,000	11,325
Kazakhstan	208.4	780,000	16,597

A multi-objective, weighting method (Loucks *et al.*, 1981) was formulated to compute net benefits to the basin countries under the conditions described above for the various coalitions. The objectives of the countries include: supplying power to Kyrgyzstan (minimizing deficits from energy demand) and irrigation water to Tajikistan, Uzbekistan and Kazakhstan (maximizing agricultural profit). The nonlinear model was programmed in the General Algebraic Modeling System (GAMS) language (Brooke *et al.*, 2006). The objective function is formulated as:

$$Maximize\ Z = -w_{Kg}\sum_{t=1}^{12}\left(\frac{E_{demand}^{t} - E_{hydro}^{t}}{E_{demand}^{t}}\right)^{2} + w_{Kg}\frac{P_{Kg}Area_{Kg}}{Max\_Profit_{Kg}}$$

$$+ w_{Tj}\frac{P_{Tj}Area_{Tj}}{Max\_Profit_{Tj}} + w_{Uz}\frac{P_{Uz}Area_{Uz}}{Max\_Profit_{Uz}} + w_{Kz}\frac{P_{Kz}Area_{Kz}}{Max\_Profit_{Kz}}$$

where E^{t}_{demand} is Kyrgyzstan's monthly hydropower demand (kWh), E^{t}_{hydro} is Kyrgyzstan's monthly hydropower production (kWh), P_i (\$/ha) is the agricultural net margin (\$/ha) and $Area_i$ is the agricultural area (ha) and Max_Profit_i is the maximum possible annual profit (\$) for each country i. The nonnegative weights w_{Kg}, w_{Tj}, w_{Uz} and w_{Kz} represent the relative importance of satisfying the various objectives of the countries; have values less than one and collectively sum to one.

The model contains constraints for mass balance on storage in Toktogul and Kayrakum reservoirs for each month. The model also includes flow balance constraints for each diversion and return flow point along the river. The energy generated in

Toktogul and Kayrakum reservoirs is a nonlinear function of the water in storage in the reservoir. The run-of-the-river reservoirs in the Naryn cascade have a linear relationship for energy generation.

We assume that Tajikistan does not have an appreciable demand for Kayrakum hydropower. Therefore, if Tajikistan is acting independently to maximize their benefits from irrigation, hydropower is not generated, since Tajikistan takes it irrigation water directly from the reservoir. If Tajikistan is acting in a coalition, then releases through Kayrakum generate hydropower that is shared with Uzbekistan and there is an associated operation and maintenance cost of \$0.01 per kWh of producing this power.

This model only considers a single year of flow and does not consider multi-year storage in the reservoirs. Several tributaries, including the larger tributaries of the Kardarya and Chirchik Rivers, and the smaller Angren and Keles Rivers, are neglected because they are not directly specified in the Agreements. The Draft Agreement deals with the incremental agricultural and power benefits gained from the Naryn River flows. Additionally, the benefits from flood control downstream in Kazakhstan are not considered. Re-operation of the Kyrgyzstan dams to store winter flows to provide downstream flood control benefits is also not considered here.

Five categories of water-type years, *Very Wet, Wet, Normal, Dry*, and *Very Dry*, are used to represent hydrologic patterns in the Syr Darya basin, corresponding to different hydrologic exceedance probabilities. A frequency analysis of the annual inflow record of 1911-2008 at the Naryn gauging station on the Naryn River (the main tributary of the Syr Darya flowing into Toktogul reservoir) were used to estimate hydrologic-level sequences used in calculating benefits of cooperation from implementing the proposed revisions to the 1998 treaty (see Figure 3 and Table 5).

Table 5. Flow Conditions, Exceedance Probability Ranges, and Corresponding Flows for Inflow to Toktogul Reservoir, Kyrgyzstan.

Condition	**Probability (%)**	**Flow (million m^3)**
Very Low	95-100	8378 - 6525
Low	75-95	10141 - 8378
Average	30-75	12872 - 10141
High	10-30	14853 - 12872
Very High	0-10	20725 - 14853

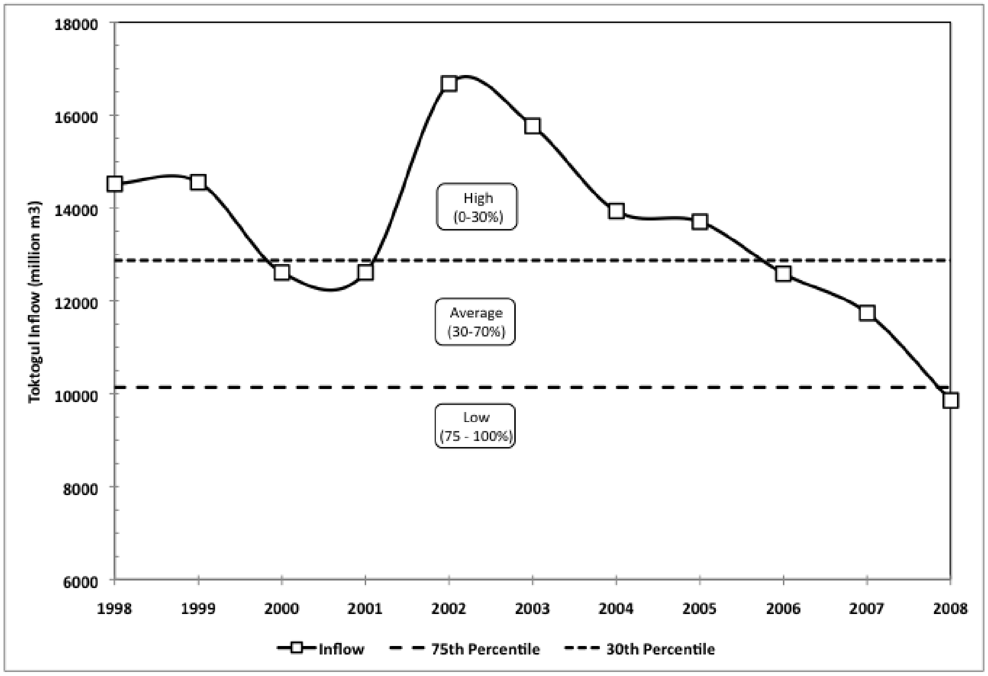

Figure 3. Annual Inflows to Toktogul Reservoir 1998 – 2008 (million m^3).

CHARACTERISTIC FUNCTIONS AND THE CORE

The values, or characteristic functions, for the fifteen coalitions described above were calculated using the river basin model. The results from the model for the non-cooperative coalitions are listed in Table 5. For this case, Kyrgyzstan has the benefit of the foregone energy cost, representing the cost to Kyrgyzstan if they had to purchase enough power to cover their demand from the market at a price of \$0.08 per kWh. The hydropower generation cost is the operation and maintenance cost of producing hydroelectricity at a cost of \$0.01 per kWh. The deficit energy cost is the cost purchasing power to cover a deficit if hydropower does not satisfy the demand. The total benefit is the agricultural profit plus the difference between foregone energy cost and total energy cost. The value or characteristic function of this coalition is \$773 million or $v(\mathrm{Kg}) =$ \$773 million. The downstream countries each maximize agricultural profit with the water available to them. Clearly, the non-cooperative situation represents a difficult situation for the countries since Kyrgyzstan is facing a net \$13 million out of pocket expense for the year and the downstream countries have very low agricultural profits.

Table 5. Value of Non-Cooperative Coalitions

Country	**Category**	**Amount (million $ US)**
Kyrgyzstan	Foregone Energy Cost	898
	Energy Generation Cost	112
	Deficit Energy Cost	16
	Total Energy Cost	128
	Agricultural Profit	3
	Total Benefit	773
Tajikistan	Total Benefit	12
Uzbekistan	Total Benefit	81
Kazakhstan	Total Benefit	19

For the two-country Kyrgyz-Uzbek coalition {Kg, Uz}, Kyrgyz summer releases to cover Uzbekistan's irrigation demand result in an energy deficit (see Table 6). Surplus energy produced from these releases is sent to Uzbekistan where it is sold. Uzbekistan, in return, compensates Kyrgyzstan for their energy deficit. The value of this coalition is *v*(Kg, Uz) = $1,076 million. A mechanism does not exist to restrict diversion to the non-coalition countries of Tajikistan and Kazakhstan. Tajikistan and Kazakhstan have increased irrigation benefits, but these benefits are not included in the value of the coalition.

Table 6. Kyrgyz-Uzbek Coalition {Kg, Uz}

Country	**Category**	**Amount (million $ US)**
Kyrgyzstan	Foregone Energy Cost	898
	Hydro-Energy Generation Cost	113
	Deficit Energy Cost	400
	Total Energy Cost	113
	Agricultural Profit	9
	Total Benefit	794
Tajikistan	Total Benefit	41
Uzbekistan	Agricultural Profit	277
	Surplus Energy from Kyrgyzstan	406
	Compensation to Kyrgyzstan	400
	Total Benefit	283
Kazakhstan	Total Benefit	63
Coalition	Value	1,076

In the Kyrgyz-Tajik–Uzbek coalition {Kg, Tj, Uz}, the Kyrgy's release water to meet Uzbekistan's agricultural demands. Surplus energy is sent to Uzbekistan, who sell it on the market for a profit of $406 million and compensate Kyrgyzstan $400 million to cover their energy deficit (Table 7). Tajikistan also sends their hydro-energy to Uzbekistan who sells it for a profit of $100 million and splits this profit with Tajikistan. The value of this coalition, *v*(Kg, Tj, Uz), is $1,206 million.

Table 7. Three country coalition {Kg, Tj, Uz}

Country	**Category**	**Amount (million $ US)**
Kyrgyzstan	Foregone Energy Cost	898
	Hydro-Energy Cost	113
	Deficit Energy Cost	400
	Total Energy Cost	113
	Agricultural Profit	9
	Total Benefit	794
Tajikistan	Agricultural Profit	41
	Hydro-Energy Cost	13
	Compensation from Uzbekistan	50
	Compensation from Kazakhstan	0
	Total Benefit	78
Uzbekistan	Agricultural Profit	277
	Surplus Energy from Kyrgyzstan	406
	Compensation to Kyrgyzstan	400
	Surplus Energy from Tajikistan	100
	Compensation to Tajikistan	50
	Total Benefit	333
Kazakhstan	Total Benefit	63

The results for the Grand Coalition {Kg, Tj, Uz, Kz} are presented in Table 8 where, Kyrgyzstan releases water in the summer to maximize downstream agricultural production in all of the other countries. As a result, there is an associated deficit energy cost for Kyrgyzstan. For this coalition the surplus hydro-energy produced by the summer releases is sent to Uzbekistan and Kazakhstan, who in turn sell the energy for $406 million. Additionally, Tajikistan produces hydropower and sends it to Uzbekistan and Kazakhstan and sold for $100 million and the profits are split between the three countries. The value of this coalition is the sum of the total benefits for each country for a total value of $1,269 million.

Table 8. Results for the Grand Coalition {Kg, Tj, Uz, Kz}

Country	**Category**	**Amount (million $ US)**
Kyrgyzstan	Foregone Energy Cost	898
	Hydro-Energy Cost	113
	Deficit Energy Cost*	400
	Total Energy Cost	113
	Agricultural Profit	9
	Total Benefit	794
Tajikistan	Agricultural Profit	41
	Hydro-Energy Cost	13
	Compensation from Uzbekistan	25
	Compensation from Kazakhstan	25
	Total Benefit	78
Uzbekistan	Agricultural Profit	277
	Surplus Energy from Kyrgyzstan	203
	Compensation to Kyrgyzstan	200
	Surplus Energy from Tajikistan	50
	Compensation to Tajikistan	25
	Total Benefit	305
Kazakhstan	Agricultural Profit	63
	Surplus Energy from Kyrgyzstan	203
	Compensation to Kyrgyzstan	200
	Surplus Energy from Tajikistan	50
	Compensation to Tajikistan	25
	Total Benefit	91

*Covered by compensating payments from other countries

The characteristic function for each coalition outlined above are shown in Table 9 and used to define the Core of the cooperative game. The Core is a set of allocations of the benefits to each countries such that no country will receive an allocation less than what they can gain by themselves without cooperation. The Core allocations are not dominated by any other allocation, meaning that every country is willing to accept the allocation (Gillies, 1953). Acceptable allocations have three necessary conditions; 1) efficiency - all coalition benefits are distributed to the coalition countries; 2) individual rationality - allocations are more than could be gained independent action; and 3) Pareto optimality - allocations sum to the value of the coalition (Gillies, 1953). The Core provides bounds on the maximum that each country can expect to receive through cooperation and negotiation (Gilles, 1953). The Core of the Syr Darya game is shown in Table 10.

Table 9 Characteristic Functions of the Syr Darya Cooperative Game

Coalition	**Characteristic Function Value (million $ US/yr)**
v(*Kg*)	773
v(Tj)	12
v(Uz)	81
v(Kz)	19
v(Kg Tj)	784
v(Kg Uz)	1,076
v(Kg Kz)	863
v(Tj Uz)	186
v(Tj Kz)	30
v(Uz Kz)	99
v(Kg Tj Uz)	1,205
v(Kg Tj Kz)	803
v(Kg Uz Kz)	1,140
v(Tj Uz Kz)	204
v(Kg Tj Uz Kz)	1,269

The Core is useful for understanding transboundary river basin water sharing agreements because it provides bounds for possible negotiation, and it improves a country's benefit beyond their non-cooperative standing. In the Syr Darya game, the lower bound (Table 10) for each country is the minimum they would require to cooperate, whereas the upper bound is the maximum they could expect to receive through further negotiation. For example, the characteristic value of the Grand Coalition, *v*(Kg,Tj,Uz, Kz), is \$1,269 million. Kyrgyzstan could try to negotiate to receive up to \$1065 million in benefits, but the minimum they would accept would be \$773 million. Given the four-dimensional Core in the Syr Darya game, there are many allocations or negotiating positions available to the countries. Cooperative game theory allocation concepts can be useful in illustrating the benefits of various negotiating positions. Some of these allocations are discussed below.

Table 10 Boundaries of the Core for the Syr Darya Cooperative Game

Country	**Lower Bound (million \$ US/yr)**	**Upper Bound (million \$ US/yr)**
Kyrgyzstan	773	1,065
Tajikistan	12	129
Uzbekistan	81	466
Kazakhstan	19	64

ALLOCATIONS

Game theoretic methods exist for selecting a single allocation from the Core. We consider two allocation methods; the Shapley value and the Nucleolus. These methods use different concepts to calculate a single allocation. The Shapely value distributes the gains of a coalition to individual countries based on their marginal contribution to that coalition (Shapley, 1953) as it enters into a forming grand coalition. For a total of n countries in a game, the Shapley allocation, φ_j, for country j is

$$\varphi_j = \frac{1}{n!}\sum_{j\in S}\left((s-1)!(n-s)!\left[v(S)-v(S-j)\right]\right)$$

where s is the number of players in a coalition S. The characteristic function for coalition S is $v(S)$ and $v(S-j)$ is the characteristic function without country j. The Shapley equation considers all coalitions containing country j. All orderings of the countries in the Grand Coalition have the same probability of occurring, namely, $\frac{(s-1)!(n-s)!}{n!}$. When country j joins a coalition, they are awarded the marginal benefit of $\left[v(S)-v(S-j)\right]$. The Shapley allocation for a country is the average of all of the marginal benefits from the ways it can join the Grand Coalition. The Shapley allocations are shown in Table 11.

Another method for selecting an allocation from the Core is the Nucleolus. The Nucleolus is calculated by finding a vector of allocations $\Phi = (\phi_1, \phi_2, \ldots, \phi_n)$ that minimizes the maximum of excesses, $e(\Phi, S)$, over all coalitions S subject to $\sum_j \phi_j = v(N)$. Where ϕ_j is an allocation to country j and all allocations, ϕ_j, must sum to the value of the Grand Coalition, $v(N)$. In practical terms, the Nucleolus minimizes the dissatisfaction of the members in the most dissatisfied coalition (Straffin, 1993). The Nucleolus can be calculated as a linear programming problem and the results for the Syr Darya game are shown in Table 11.

The monetary profits from cooperation in the grand coalition are shared among the participating countries. Both the Shapley and nucleolus allocations lie within the core d in Table 10. Each country receives an increased benefit through cooperation, as shown with the Shapley and nucleolus allocations (Table 11). Uzbekistan receives the largest allocation beyond their independent allocation under both methodologies. This can be attributed to their large agricultural production, as well as their ability to sell the surplus energy on the market.

An interesting note is Kazakhstan's allocation. Kazakhstan receives $40 million with the Shapley allocation and $41.5 million with the nucleolus. Kazakhstan earned larger profit than both of these allocations when they are not participating in a coalition such as the Kyrgyzstan-Uzbekistan coalition (Table 6) or the Kyrgyzstan-Tajikistan-Uzbekistan coalition (Table 7). In both of these coalitions, Kazakhstan was able to gain $63 million since there is not a method for limiting diversions to non-coalition countries. The $63 million is near the upper bound of the core for Kazakhstan. This result may change if flood control provided from retiming reservoir releases were included.

In addition to the monetary allocations, the water allocations are shown in Table 11. The water allocations are calculated as a percentage of the total water allocated, rather than the percentage of Toktogul releases. As might be expected, under the Grand Coalition, Uzbekistan and Kazakhstan have the largest allocation of water. These large allocations are due to the agricultural production in the two lower basin countries. These two countries produce the largest profit from water allocations.

Table 11. Benefit Allocations in the Syr Darya Game

Country	Independent allocation (million $/yr)	Allocated Water	Allocated Water	Shapley allocation (million $/yr)	Δ Shapley allocation (million $/yr)*	Δ Shapley allocation (%)*	Nucleolus allocation (million $/yr)	Δ Nucleolus allocation (million $/yr)**	Δ Nucleolus allocation (%)**
		(million m^3/yr)	(%)						
Kyrgyzstan	773	665	4.5	913	140	72.0	844	71	66.5
Tajikistan	12	1197	8.2	60	48	4.75	34.5	23	2.7
Uzbekistan	81	7193	49.1	256	175	20.2	349	268	27.5
Total	885	14,639	100	1,269	384	100	1,269	384	100

* Increase in country's allocation of benefits under the Shapley allocation relative to the independent allocation.

** Increase in country's allocation of benefits under the Nucleolus allocation relative to the independent allocation.

STABILITY

Once an allocation is chosen from the core, the stability of the allocation can be calculated which measures each country's satisfaction with the allocation. The Gately propensity to disrupt measures the loss that a country can cause on other countries by leaving the Grand Coalition. The propensity to disrupt is a measure of a country's negotiation strength for improving their allocation from the Grand Coalition. The value compares what an individual country stands to lose by leaving the Grand Coalition compared to what the remaining countries in the grand coalition lose having that country leave. The greater the loss to the grand coalition compared to the loss of the individual country, the more likely the country is to leave the grand coalition if their share is not increased. The Gately "propensity to disrupt" (d_j) of player j is calculated as (Gately, 1974):

$$d_j = \frac{\sum_{i \neq j} \Omega_i - v(\{N - j\})}{\Omega_j - v(\{j\})}$$

Where:

Ω_j = allocation to player j

$\sum_{i \neq j} \Omega_i$ = the sum of the allocation to all players $i \neq j$

$v(j)$ = characteristic function for the non-cooperative for player j

$v(N\text{-}j)$ = characteristic function for the Grand Coalition without player j

If d_j is positive and larger than a specified value, player j has a tendency to disrupt the Grand Coalition unless his allocation is increased. The propensity to disrupt represents the ratio of what the players in coalition $\{N - j\}$ would lose if player j left the Grand Coalition, to what the player j would lose by leaving the Grand Coalition. The propensity to disrupt is used to eliminate imputations in the Core for which a player's propensity to disrupt is higher than a specified value.

Table 12 shows the propensity to disrupt for each country for both the Shapley and the Nucleolus allocations. Looking at the propensity to disrupt for Tajikistan under the Shapley allocation, Tajikistan has a propensity to disrupt of 1.42. If Tajikistan decides to leave the grand coalition they will lose a total of $48 million since they forego the Shapely allocation for their non-cooperative value. The other countries in the Grand Coalition stand to a total of 1.42 times the $48 million loss that Tajikistan received by exiting the coalition. Kyrgyzstan has the lowest propensity to disrupt indicating that there are more satisfied with their Shapley allocation.

Table 12. Gately Propensity to Disrupt for Syr Darya Shapley and Nucleolus Allocations

Country	Shapley Allocation	Nucleolus Allocation
Kyrgyzstan	1.08	3.11
Tajikistan	1.42	4.20
Uzbekistan	1.20	0.44
Kazakhstan	1.18	1.00

The Shapley allocation is more stable than the nucleolus allocation. Kyrgyzstan and Tajikistan have a tendency to disrupt the grand coalition as denoted by their high propensity to disrupt. The nucleolus allocates a greater share of the coalition value to

Uzbekistan to minimize their propensity to disrupt, however, by increasing Uzbekistan's share of coalition gains; it decreases Kyrgyzstan's and Tajikistan's allocations.

CONCLUSIONS

The purpose of this paper was to demonstrate that cooperative game theory can be used as a tool to quantify the benefits of cooperation among riparian nations with respect to water resources in a transboundary river basin. The cooperative game theory analyses on the draft agreement, "Improvement of Shared Water Resources Management in Central Asia" demonstrates that there are increased economic benefits to all countries in the Syr Darya basin if they follow the cooperative arrangements outlined in the agreement. The Shapely allocation provided each country with an increased economic benefit. This allocation was also shown to be stable with respect to each country's propensity to disrupt. The cooperative game theory concepts in this paper can be used as the basis for treaty negotiations. Each country can clearly see the benefits associated with following the draft agreement. Additionally, each country understands what the bounds on their allocation are based on the core concept.

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