Municipal Risk and Time Preferences in Western Water Transactions

By

Rowan Mansi Isaaks

A Thesis Submitted to the Faculty of the

DEPARTMENT OF AGRICULTURAL AND RESOURCE ECONOMICS

In Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

2018

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SIGNED: **Rowan Mansi Isaaks**

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This thesis has been approved on the date shown below:

B M Colby 4/26/18

Dr. Bonnie Colby Date

Professor of Agricultural and Resource Economics

ACKNOWLEDGEMENTS

There are several people that deserve acknowledgement for their help in making this thesis successful. Special recognition goes to my thesis committee: Dr. Bonnie Colby, my primary advisor, for her guidance on this complex topic, and Dr. George Frisvold and Dr. Gary Thompson for their comments and insights. Additionally, many thanks to Ryan Young for his help with data collection, Dr. Dan Scheitrum for his thoughts on game theory models, and the many water professionals that have given their indispensable input.

Acknowledgement of financial support for this work goes to the following entities: The United States Bureau of Reclamation (BOR), Climate Assessment for the Southwest (CLIMAS), United States Department of Agriculture – National Institute of Food and Agriculture (USDA – NIFA), and The Walton Family Foundation (WFF).

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Abstract

Markets for water rights have the potential to increase allocative efficiency of perhaps the scarcest natural resource in the western United States. Due to several features of markets in the region, they are best modeled by game theory. The Rubinstein Bargaining Model can be appropriately adapted to the case of bilateral negotiations for water rights, and predicts that the time preferences of players impact the outcome. It is also possible to model the effect of risk and municipal risk preferences relating to the available supply of water, which microeconomic theory predicts will also affect outcomes. While previous literature has written about various determinants of water market outcomes, little attention has been paid to the empirical measurement and testing of the effect of time preferences and risk in these markets. In this thesis, I attempt to bridge this gap between the theory and empirical analyses by testing theoretical predictions using both a well-known data set and a novel one. I find moderate evidence suggesting that a greater time preference results in a less favorable outcome, and that buyer risk-aversion is a disadvantage in bargaining when risk is present.

Chapter 1: Introduction

Over the past several decades, increasing drought frequency and severity combined with rapid population growth in the western United States has led to increased water scarcity in an already arid region. Water rights transactions,[1] particularly agricultural-urban ones, have been touted by many as a policy tool for allocating water to a higher valued use, generating gains from trade and improving allocative efficiency. However, water markets are characterized by many deviations from classical competitive markets, and alternative theoretical approaches are necessary to provide a meaningful framework for understanding their structure and performance. In standard microeconomic theory, time and risk preferences are regularly noted as key factors that can influence preferences and decision making of economic agents. However, there is no literature empirically testing hypotheses regarding risk and time preferences derived from suitable non-cooperative games in the setting of water markets. In this thesis, I first model a bilateral negotiation concerning the price of a water right transaction from an agricultural seller to an urban buyer using a non-cooperative bargaining model. Then I empirically test predictions regarding time preference, outside options, and risk where possible, focusing on the preferences of the urban buyer, using both an established dataset and a novel one.

The remainder of this thesis proceeds as follows: In chapter 2, I explain the motivation for water rights markets from the economic perspective, explore barriers that often prevent

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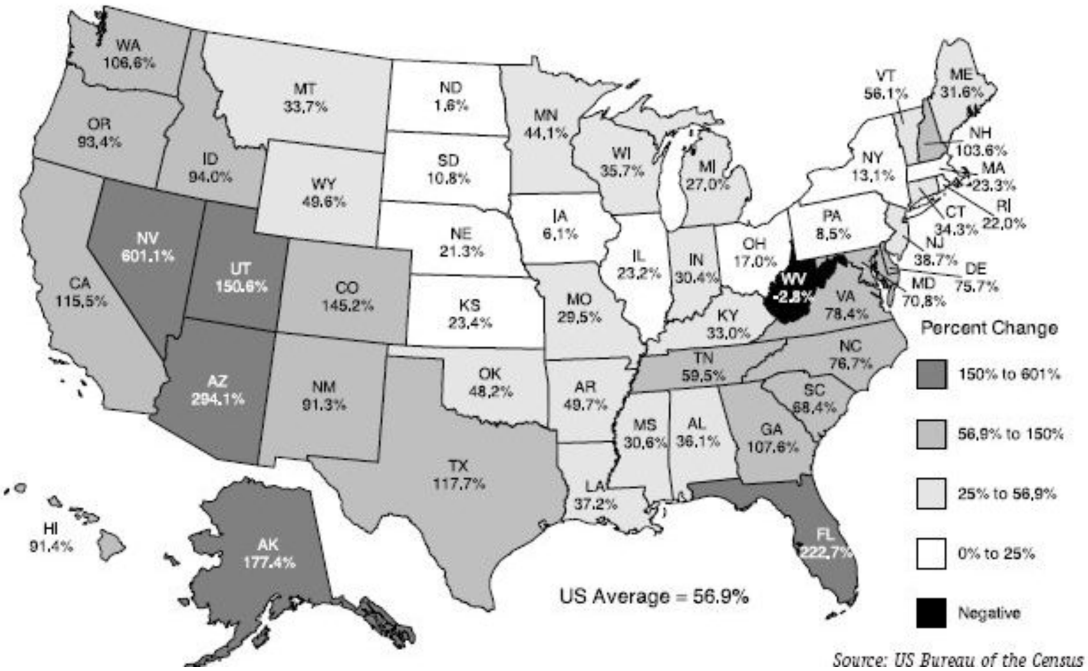
[1] 'Transactions' here refers to both temporary leases and permanent sales of water rights. This thesis also uses the term 'transfers', which refers more to the physical movement of water from one place and/or use to another, rather than the negotiated agreement itself.

transactions from occurring, and highlight the microeconomic factors that are the topic of this thesis. Chapter 3 introduces the rationale for using game theory as a theoretical framework for analyzing outcomes in water markets, and then develops the model that I use in my analysis. I start by justifying my adaptation of the Rubinstein Bargaining Model, then I work through the model in the context of water markets and introduce risk into the model. Finally, I summarize the main predictions of interest that are derived from the theoretical model. Chapter 4 summarizes previous empirical work and introduces the data sources and variables used in the analysis. Chapter 5 contains econometric testing of some predictions derived in chapter 3, using price as the outcome variable. Data from two sources and three Western U.S. states is utilized from the periods 2002-2009 and 2012-2016. Potential econometric issues such as endogeneity are also addressed. Finally, chapter 6 summarizes findings, discusses implications, and comments on potential future avenues of research. I find moderate support that a greater time preference and relative risk-aversion (when supply from a source is uncertain) are disadvantages in bargaining for urban buyers.

Chapter 2: Agricultural-Urban Water Transactions

Motivation for Transactions

When analyzing any economic transaction, an economist reasonably inquires: Why does this transaction exist? What is the economic rationale that logically facilitates it? In the case of water rights transactions in the western United States, the changing balance of supply and demand is the fundamental driver. The Colorado River and its tributaries are the largest single source of water in the Southwest. For the last several decades, supply from the Colorado River (and many other natural water sources) has been declining due to climate conditions in the region (USBR, 2012). In a recent study, Udall and Overpeck (2017) found that flows in the Colorado River have been around 20% lower in the 21st century so far compared to the 20th century, and that around 1/3 of this decline is due to increased temperatures in the region, with the remaining 2/3 being due to lower precipitation levels. On the other side, demand for water has been rapidly increasing, mainly due to population increases in urban areas such as Denver and Phoenix, although water conservation efforts and economic recession in the last decade have caused demand to stagnate. Figure 1 shows that the West was the fastest-growing region in the United States over the second half of the 20th century, and has continued that growth rate (U.S. Census Bureau, 2013). The combination of varied and steadily decreasing supply with increasing urban demand has led to a shortage of water in some areas. Figure 2 shows the historical trend of the supply/demand balance in the Colorado River Basin (USBR, 2012). Figure 2 was produced in 2012, and projects out into the future. However, more recent predictions for future supply, which are much more pessimistic than what is shown in Figure 2, conservatively estimate that flows in the Colorado River will be reduced by 20% by mid-century (cited in Udall & Overpeck, 2017).



Source: US Bureau of the Census

Figure 1: Population change 1960-2000 by state (%)

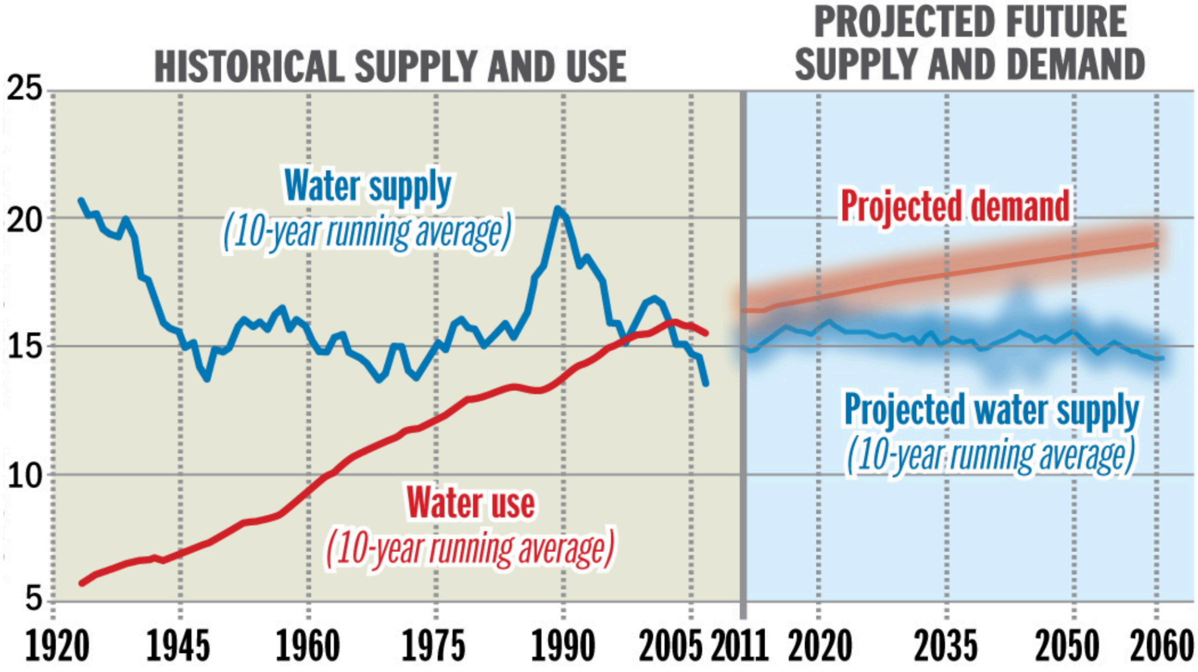


Figure 2: Historical/Projected Supply and Demand in the Colorado River Basin

When demand exceeds supply, an allocative mechanism is required. Most western states use a system called prior appropriation (or a hybrid of prior appropriation and other water rights systems), which is essentially a first-come first-serve system: Under prior appropriation, the first person/entity to ‘beneficially’ use water from a given water source has the right to continue using that amount of water, in the same place and for the same purpose. This system means that the ‘seniority’ of a water right is often its most important attribute, which is essentially a priority number to divert water. Those with a lower priority number cannot divert their water allocation until those with a higher number have been assured of their allocation for the current season. Historically, since the first colonists and frontiersmen to settle the West created agricultural communities, it is still the case that farmers and ranchers hold the lion’s share of senior water rights in the region.[2]

In most western U.S. states, water rights received under prior appropriation can be bought, sold, and leased. Differing marginal value of use between different sectors creates the incentive for mutually beneficial trades. In the remaining sections of this chapter, I will characterize the nature of the transactions that occur in western U.S. water markets, as well as describing markets of note and issues that arise when transferring water.

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[2] Of course, First Nations communities were beneficially using water long before Europeans ventured westward. However, it has only been in recent years that the U.S. government has begun recognizing and affirming water rights for these communities retroactively. The study of these water rights and transfers involving First Nations’ water rights is an interesting topic, but is not discussed further in this thesis.

Barriers to Transactions

In principle, there exists an optimal set of transactions that would maximize the total economic surplus generated by water in a specific period and geographic area. However, many hypothetically beneficial transactions are prevented due to barriers to trade. The first and most obvious barrier to potential transactions is conveyance. On a per-unit weight scale, water is not valuable. Therefore, to make a transaction financially feasible, sufficient physical or natural conveyance must exist to divert water to a proposed new place of use. For a surface water right, the simplest case of this occurs when the buyer is upstream/downstream from the seller on the same river system, in which case either the buyer diverts the water before it reaches the original point of diversion, or the seller lets the transferred water flow downstream to the buyer. For a groundwater right, this might occur where two users reside in the same aquifer system, in which pumping permits can be traded freely. However, many hypothetical mutually-beneficial transactions are not of this kind, and require man-made infrastructure to facilitate them. The early to mid 20th century saw the construction of numerous pipelines, ditches, and other conveyance structures. This period began with the 1902 Newlands Act and the creation of the Bureau of Reclamation (BOR), and continued for several decades (USBR, n.d.). This conveyance infrastructure allowed water to be delivered across mountains and between basins, greatly widening the universe of potential transactions. Despite this, many potential trades still are prevented due to physical constraints. This fact provides insight into defining feasible transaction markets, which will prove useful for identification purposes when testing predictions econometrically.

Transaction costs represent another common barrier to transactions (Colby, 1990). Because completing a transaction requires factoring in hydrological and legal concerns relating to the prior appropriation doctrine, there is often a complex and/or lengthy process required to officially transfer water rights, which potentially necessitates hiring hydrologists, engineers, and lawyers. Naturally, these expert services are not cheap. Navigating the legal process can take months or even years, so the loss of time can be a non-monetary 'cost' of a transaction. Additionally, because not all hypothetical trading partners are feasible trading partners, a prospective buyer/seller may incur costs in searching for a trading partner (Colby, 1990). A combination of the types of transaction costs discussed here can make the difference between a cost-effective transaction and a cost-ineffective one.

The final major barrier to transactions is the potential for third-party effects. Traditional 'buy-and-dry' transactions, where land is fallowed after the associated water rights are sold out of the area, can cause associated negative effects to the (mainly agricultural) industries that provide inputs for the old use of water. Transactions like this may also mean that water is being diverted further upstream, which reduces flow in the part of the stream between the two trading parties. The sale of water rights by a relatively upstream user will influence users downstream, as they partially depend on return flows from the upstream user's diversions for their water. Not only does this affect downstream agricultural operations, but also other, non-consumptive uses of water. It is well established in the environmental economics literature that society places a value on the existence of water in the environmental and recreational dimensions. Authorities that govern water transactions will often either restrict transactions that create significant third-party effects, or mandate that third-parties be paid compensation, which is essentially another transaction cost for water buyers and sellers to deal with.

The barriers to transactions discussed here are pervasive in every western state. However, a select few markets possess special circumstances that have allowed them to at least partially mitigate barriers to transactions. A model example of this is the Colorado – Big Thompson (C-BT) Project, administered by the Northern Colorado Water Conservancy District (NCWCD). The C-BT market connects water near the headwaters of the Colorado River in Colorado's West Slope and delivers it to municipal, industrial, and agricultural users on the Front Range and Northeastern Plains of the state. A little west of the Continental Divide, multiple reservoirs collect and store water from the Colorado River. Mostly by way of gravity (but also some pumps), the water flows down the East Slope to three large reservoirs on the Front Range's South Platte Basin,[3] before being released to water users within the C-BT Project boundaries (Howe, 2011). The C-BT Project is comprised of many tunnels, canals, and reservoirs, which solves the conveyance problem for a specific set of users in the defined region, allowing around 210,000 acre-feet of water to be delivered ever year.

The key to the low transaction costs of the C-BT Project market is a legal one; the project water introduced into the South Platte was 'new' in the legal sense. NCWCD owns the rights to all return flows of project water. This means that water users attempting to purchase C-BT water rights do not have to go through the costly legal process of proving 'no injury' as is

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[3] The C-BT Project also contains six power plants that generate around 770 million kilowatt-hours of hydroelectric energy a year, most of which is produced when C-BT water flows down the East Slope through the generators. Only 70 million kilowatt-hours a year are required to operate the C-BT pumps, so the rest is sold to other areas of Colorado and users in adjacent states (Northern Water, n.d.).

typically required in Colorado (Howe, 2011). All that is required to administratively process a transaction of C-BT rights is a small application fee and the approval of the NCWCD. That is not to say that there are not any third-party effects whatsoever, merely that from the current legal perspective, no action need be taken to mitigate third party effects by the transacting parties. These possible lingering externalities have received some attention in the literature (Howe & Goemans, 2003), but are not discussed further in this thesis.

Buy-and-dry transactions are appealing to many municipalities and industries because they are viewed as a prudent investment and are easily scalable to acquire the volumes of water desired. However, as market activity has expanded in the West, policymakers have begun to investigate different ways of transferring the use of water between parties in ways that dampen third-party effects to agricultural communities. In Colorado, this has led to the development of the Alternative Transfer Mechanisms (ATM) Program, which funds pilot projects and studies into the feasibility of contracts that transfer water out of agriculture on a temporary and/or intermittent basis. These contracts typically require the water right owner to adopt some new farming practice that reduces farm consumptive use, and then that excess water is transferred to the buyer per the contract terms. Methods for generating this surplus include rotational fallowing, deficit irrigation, and crop switching. Since adoption of these methods will inevitably lead to a decrease in profits from farm operations, additional compensation should be incorporated into the contract terms. As of 2016, at least 35 separate grants had been awarded for pilot projects and research into ATMs (*WestWater Research*, 2016) and the state of Colorado is aiming for ATMs to provide at least 50,000 acre-feet per year, However, it is still the case generally that traditional “buy and dry” transfers are the most attractive option to municipalities (Castle et al., 2016), and so it is likely that they will continue to be the main feature of water markets in Colorado and throughout the West.

In-Negotiation Factors Affecting Water Transactions

In this section, I will discuss some important factors that can affect the outcomes of negotiations for water rights. As was discussed earlier, the physical landscape, conveyance infrastructure and institutional rules in a region determines the universe of potential transactions. When thinking about the archetypal agricultural-urban transaction universe, the feasibility of a transaction is limited by the presence of conveyance facilities linking the agricultural water source to the municipality. Thus, the location of these buyers and sellers relative to each other dictates their outside options, an element of market power in negotiations. Imagine a situation where a large city exists in the middle of a large agricultural region, with no other cities in proximity. This creates a geographic monopsony where the city has a credible threat in the form of outside options (transactions involving other farms) that will enhance its bargaining position with a particular farm. On the other hand, consider a region that contains many cities within a short distance of each other and one large irrigation district. In this case, the irrigation district has monopoly power over the cities. A full spectrum of realities between these two cases exists, and where a given water market falls on this monopsony-monopoly spectrum affects the nature of outcomes in that market. Emerick (2007) has previously investigated this issue and found ‘mixed’ evidence of this effect. Additionally, there is extensive coverage of this topic in the environmental science literature relating to the “Best Alternative to a Negotiated Agreement’, or BATNA framework. The BATNA provides a lower bound on acceptable terms of a transaction negotiation, which in the case of water transactions would be partially determined by outside options (Nyomakwa-Obinpeh, 2017).

Time preference is another important factor to consider in water market negotiations. In microeconomic theory, time preference is a relative measure of the utility obtained by receiving a good or service now compared to receiving that good or service at some future date. The discount factor of the individual/entity is a measure of their time preference. An economic agent that discounts utility in the future at a higher rate will more strongly prefer to receive a good/service now, and so will exhibit a greater time preference in their negotiating behavior (Frederick, Loewenstein, & O'Donoghue, 2002). The role of time preference on decisions relating to the possession and consumption of water is not a new idea (Griffin, 2016). However, little attention has been paid to empirically testing the impact of time preference on outcomes in water markets.

Economic agents have expectations regarding future events. However, future events in many cases involve an element of risk. Therefore, agents' risk preferences can have meaningful impacts on their behavior towards risky events. At this point, it is worthwhile to make a brief digression to make a distinction between risk and uncertainty, as these two terms are often used interchangeably, even on many occasions in economics. This point received a thorough treatment in Knight (1921): Risk occurs when the outcome of a future event is unknown, but the probability and payoff of each potential outcome is known. The most relevant example of this in water markets comes from the fact that when buyers and sellers negotiate, they are bargaining over the transfer of "paper" water that is a legal entitlement to water rather than the water itself. Therefore, based on the seniority of the right, the actual amount of water that any given right yields in a year retains a degree of risk. In this case however, bargaining parties know this and can adjust their expectations per individual risk preferences, or as Knight puts it: “Risk, in the ordinary sense, does not preclude perfect planning” (1921). Uncertainty, on the other hand, occurs when the outcome of a future event is unknown, and the probability and/or payoff of each potential outcome is *unknown*. The legal dimension of water rights encompasses the bulk of true uncertainty cases in water markets. Litigation over the right to divert water has long been a feature of western water politics, and the outcomes of court cases cannot always be predicted, especially when concerning a case that has no prior precedent. Even in cases such as the Colorado River Compact, where curtailment protocol was spelled out explicitly, uncertainty still exists because a large-scale curtailment has never been implemented, many new agreements have been crafted that affect curtailment, and there is no prior experience as to how enforceable a curtailment would be in practice, or how many lawsuits would arise from its enforcement. “Knightian” uncertainty and its effects are beyond the scope of this thesis. Ordinary risk has received some recent investigation in the water economics literature (e.g. Leroux & Martin, 2015), and its effect on water rights. The risk preferences of water market players will be discussed further in the next chapter, as well as how risk and time preference are intertwined.

Chapter 3: A Game-Theoretic Approach to Transactions

Game Theory and Water

There exist many choices for analyzing water markets from the perspective of economic theory, so naturally the question arises: Why game theory? As discussed earlier, differing marginal values of use for water between parties creates the potential for mutually-beneficial trades. However, the usual economic modeling assumptions regarding gains from trade assume that the markets in which trades occur are perfectly competitive. As seen in the previous chapter, this is not the case. Transfers of water can cause third-party effects, which limits the set of feasible transactions either directly, or indirectly through increased transaction costs (Braden, Eheart, & Saleth, 1991). Lack of experience in markets and a dearth of information for buyers and sellers lead to sub-optimal outcomes. Finally, monopoly and monopsony situations are common due to geographic and conveyance issues, which cause asymmetric bargaining power between parties (Emerick, 2007). For these reasons, this thesis will refer to “transactions” more often than to “markets”. As has been noted before, it is sensible to think about water rights transactions as closed, individual, spot-market agreements, which are ripe to be modeled by bargaining games.

Applications of game theory in the water trading arena are limited. This might be viewed as surprising by many practitioners, given the negotiation-heavy nature of many water transactions. Formally, game theory traces its roots the 1944 book by von Neumann and Morgenstern (1944). However, it was John Nash (1950) who generalized the field and laid the groundwork for the application of game theory in numerous economic settings. There exist several canonical ‘games’ that have potential application to water and water resource issues.

Madani (2010) distills this point well by finding connections between three standard games (Prisoner’s Dilemma, Chicken, Stag-Hunt) and real-world water resource issues. Although there have been numerous applications of game theory to water resources in general (Parrachino, Dinar, & Patrone, 2006), there are fewer papers analyzing water transactions specifically.

Almost all the literature applying game theory in water markets focuses on cooperative game theory models, particularly multilateral models that focus on ‘social optimality’ or fairness. Braden, Eheart, and Saleth use cooperative game theory insights to determine bargaining rules that can be implemented to produce certain social gains (1991). Tisdell and Harrison implement several n-person games to analyze the distributional effects of pre-trade allocation methods, focusing on the element of social justice (1992). Ambec and Sprumont propose and discuss a fairness requirement for agents along a river with quasi-linear preferences (2000). Kahil, Dinar, and Albiac develop a cooperative game theory framework to analyze management policies that could help manage scarcity during a drought (2015). The sole example of explicitly deriving comparative statics using a game theory model and testing these predictions is Emerick (2007), who used a bilateral cooperative Nash model. This work forms a part of the inspiration for the methods used in this thesis.

The main reasons that cooperative game theory is prevalent in the literature are that cooperative games are simple to implement and that it is easy to model transferrable utility in a cooperative model. This second point is especially useful in many conceptual and actual situations where players must decide how to share a generated surplus. However, the drawbacks of this approach are that Nash models do not reflect the back-and-forth nature of many real-life bargaining situations, the dynamics that are of primary interest for this thesis.

Non-cooperative models can address these two issues by both incorporating the alternating-offers setup and explicitly including bargaining factors such as time preference. The goal of this chapter is to derive comparative statics from a simple non-cooperative model. In the following sections, I discuss an interesting result of the cooperative Nash model, then adapt a simple non-cooperative bargaining model to the case of an agricultural-urban water rights negotiation, and finally use the equilibrium solutions of the model to derive predictions about bargaining outcomes.

Cooperative Nash Model

The original cooperative Nash Bargaining Model (NBM) was conceptualized by Nash (1950) as a treatment of the bargaining problem, specifically a non-zero sum bilateral bargaining situation. Given a set of desirable axioms, most notably Pareto-optimality, Nash derived a stationary and unique solution to the bargaining problem. Variants of the NBM have been used extensively in the economics literature spanning countless topics, including distributive justice (Binmore, 1998, 2005), employee wage negotiations (McDonald & Solow, 1981), and professional sports leagues (Szymanski, 2004). The desirability of Nash models is mainly due to two factors: The ease of implementation and the guarantee of a unique solution, the second of which is needed for deriving firm predictions. In the case of water transaction negotiations, the most relevant drawbacks of the Nash model (and other cooperative models), are that i) the dynamics of offers and counteroffers are not modelled, and ii) the potential cost of delays are ignored.

In his work on market power in water transactions, Emerick (2007) adapted the NBM to derive a prediction about the effect of market power on the price of transactions. This general approach exemplified the potential for game theory insights to generate potentially testable predictions through derivation of comparative statics. To provide some theoretical justification for implementing a simple non-cooperative model in the next section, I will selectively describe the NBM as implemented by Emerick (2007), focusing on a single 'interesting result' in the model.

In this water transaction version of the NBM, we consider two players, an Irrigation District (ID) and a Municipal Provider (MP). The ID is a coalition of agricultural producers, which is a common setup in the West.[4] The ID's 'economic goal' in this context is to maximize profits of its constituent members from agricultural production and transactions of water rights.[5] Utilities in the United States are typically run by private companies, however, because they are effectively local monopolies, municipal policy mandates that they operate under a break-even constraint, meaning that they must charge consumers at cost for water, after allowing for reasonable profits. I characterize the MP's goal as maximizing consumer surplus, realizing that this is a rough proxy for their true goal, which is more complicated than this. The ID is assumed to possess an exogenously-determined quantity of water rights, of which it can transfer a portion to the MP. The negotiation between the ID and the MP concerns both the quantity of water to be transferred and the price of that transaction. The following parameters are implicitly defined:

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[4] Although irrigation districts are made up of individual farmers who in many cases have their own separate water rights, due to the costs of negotiations many municipal utilities will only negotiate with an ID rather than negotiate individual contracts with each farmer/producer.

[5] An alternative definition of the ID's utility, proposed by Braden, Eheart, & Saleth (1991), is that the utility derived from the water right is the sum of the agricultural yield saved from loss due to irrigation, plus any revenue gained from selling/leasing water rights.

- π = Profit accrued to ID when a transaction agreement is reached
- π_D = Profit accrued to ID when transaction agreement is *not* reached
- V = Consumer surplus obtained by MP when a transaction agreement is reached
- V_D = Consumer surplus obtained by MP when a transaction agreement is *not* reached

π_D and V_D are referred to as the disagreement payoffs for the ID and the MP respectively, analogous to the baseline scenario.

Now we look at two separate cases. The first, simplistic case assumes that the ID and the MP are in fact one single entity. In this case, the aggregate entity must choose a portion of the ID's original endowment to transfer to the MP to maximize the summed benefits (B) of the parties:

$$Max\ B = \pi + V$$

Next we go back to the cooperative game with two distinct entities. The classic solution to the NBM involves maximizing the Nash Product (N), which is essentially the product of the net gains from the transaction with respect to price and quantity:

$$Max\ N = (\pi - \pi_D)(V - V_D)$$

Finally, we compare these two cases. Note that by default in the single-entity case, the Pareto-optimal amount of water to transfer will be selected, by virtue of the entity maximizing total benefits. This quantity is the point at which the marginal value of water for the ID and the MP will be identical. However, Emerick (2007) showed that, like in many cooperative games, the Nash bargaining solution also results in a Pareto-optimal quantity being transferred. Therefore, the interesting result is that in the Nash setup, regardless of whether the ID and the MP are the same entity or different ones with competing interests, there exists one single Pareto-optimal quantity that will be transferred. I will now utilize this fact to set up a simple non-cooperative model.

Rubinstein Bargaining Model

The classic Rubinstein Bargaining Model (RBM) is a bargaining game with alternating proposals and an infinite timeline, developed by Ariel Rubinstein, who found a solution for the infinite alternating model in his 1982 paper “Perfect Equilibrium in a Bargaining Model”. The original model involves two players with perfect information deciding how to split a ‘pie’ of size 1. An intuitive appeal to adopting the Rubinstein model is that it can imitate the back-and-forth nature of many bargaining situations, which is a key feature in the world of water rights negotiations. The RBM setup is slightly different from that of the water rights transaction, where there are two variables to be decided, quantity and price. Therefore, our framework requires some alterations if we are to utilize the Rubinstein model. Fortunately, as we saw from the cooperative Nash model, the equilibrium quantity transferred in the 2-player asymmetric game is identical to the quantity transferred when the ID and the MP are a single entity. Therefore, I will set up a very similar game but slightly adapt it to fit a scenario where the Pareto-optimal quantity to be transferred is assumed, and bargaining takes place over price solely. This assumption is examined later through econometric tests for endogeneity of quantity in the empirical models.

As in the regular RBM, we have two players with perfect information, the Irrigation District and the Municipal Provider, representing the archetypal agricultural-urban transaction. These two players are deciding on a price to transfer the rights, a fixed quantity of water from the ID to the MP. This quantity is assumed as given, based on the results derived in the cooperative Nash model earlier. We can still think of splitting a pie of size 1 as in Rubinstein's original model. However, for our purposes, the share of the pie going to the ID represents an ordinal price on a scale between 0 and 1 that the ID receives for their water rights. Zero represents the case where the rights are given away for free by the irrigation district, and 1 represents some arbitrarily large price (such as the MP's upper limit on ability to pay). It is still the case that each entity wants to maximize their portion of the 'pie'. The game is characterized by infinite horizon alternating offers.[6] Starting from round 1: In each odd-numbered round of bargaining, the MP offers a price, and the ID either accepts or rejects the offer. In each even round, the ID offers a price, and the MP either accepts or rejects. If an offer is accepted, the game immediately ends. If an offer is rejected, the game continues to the next round. Each player also has a discounting factor[7] between 0 and 1 to account for the costs associated with a delay in reaching an agreement. We will define these discount factors as δ_{ID} for the ID and δ_{MP} for the MP. With this definition, a player with a smaller value for their discount factor is hurt more by delaying a price agreement. A simpler case of the RBM occurs when the two players have the same discount factor, although the results from this game are not quite as illuminative. In our case, it seems quite reasonable to assume that the Irrigation District and the Municipal Provider would have different discount rates. Their reasons for desiring a transaction

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[6] Obviously, the exact details of how a negotiation proceeds are heterogeneous. For example, the municipal provider may offer continuously-increasing offers for a water right until the Irrigation District is enticed to sell, a rather one-sided negotiation setup. The alternating rounds feature is desirable though because offers are typically not immediate, often requiring hydrological and legal input before an offer is made to ensure its viability.

[7] Note: Although a related concept, this is not the same as the discount factor used in benefit-cost analysis.

and penalties for failing to achieve a transaction are different, and in fact this assumption is central to this thesis itself.

The solution to the Rubinstein model is satisfying in the sense that there is a stationary solution,[8] which also is a unique solution since there are no non-stationary solutions (Rubinstein, 1982). As this is an infinite game, we cannot simply start at the end and use backward induction as is done with finite alternating games. Instead, we define a continuation value for the ID. The continuation value is simply a non-discounted amount that a given player expects to receive if no agreement is reached in the current round. Note that at this point in the model, we do not know the exactly what the continuation value is, it is just a hypothetical ordinal price that the ID expects to eventually receive if it rejects the offer from the MP in the given odd period for the ID, which we will denote as V_{ID}. At this point, we do not know what this value is, but it will be solved for shortly. The continuation value can be thought of in terms of the BATNA framework as discussed in the previous chapter, which is similar to the disagreement payoff in the cooperative Nash game (Nyomakwa-Obinpeh, 2017).

With the groundwork laid, we can set up and solve the game, which has been visualized in Table 1 and Table 2. Starting from a generic odd period (where the MP proposes and the ID responds), we say that if the ID rejects the MP's offer in the current period, the ordinal price received by the ID will be $\delta_{ID}V_{ID}$, which is the discounted continuation value for the ID. This is because in order for the MP to get the ID to accept its offer in the odd period, it must at least match the ID's discounted continuation value, otherwise it would not make sense for the ID to

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[8] A stationary solution is a solution that is derived from assuming players adopt the same strategy in every round.

accept. Thus, the MP receives the remainder of the "pie", $1-\delta_{ID}V_{ID}$, although note again that the only meaning of the pie here is the ordinal price the ID receives for a fixed quantity.

Table 1: Rubinstein Bargaining Model Solution Step 1

	Municipal Provider	Irrigation District
Even Period		
Odd Period	$1-\delta_{ID}V_{ID}$	$\delta_{ID}V_{ID}$

We then look at the even period directly preceding the generic odd period, where it is now the ID making the offer to the MP. The ID knows that if the MP rejects the offer in this round, then it will receive $1-\delta_{ID}V_{ID}$ in the next round (our original generic odd round). So in essence, this value is the MP's continuation value. Therefore, following the same logic used a minute ago, in order to get the MP to accept an offer, the ID must offer the MP's discounted continuation value, which is $\delta_{MP}(1-\delta_{ID}V_{ID})$. Thus, the slice of the "pie" that the ID receives (and the ordinal price of the transaction) is $1-\delta_{MP}(1-\delta_{ID}V_{ID})$.

Table 2: Rubinstein Bargaining Model Solution Step 2

	Municipal Provider	Irrigation District
Even Period	$\delta_{MP}(1-\delta_{ID}V_{ID})$	$1-\delta_{MP}(1-\delta_{ID}V_{ID})$
Odd Period	$1-\delta_{ID}V_{ID}$	$\delta_{ID}V_{ID}$

Now we can solve for the continuation value of the irrigation district by extending our previous logic once again: Thinking about the odd period *before* our even period, if the ID were to reject the MP's offer in that round, it could expect to receive $1-\delta_{MP}(1-\delta_{ID}V_{ID})$ in the next round, which is the very definition of the continuation value. Setting V_{ID} equal to this value allows us to then solve for V_{ID}:

$$V_{ID} = 1 - \delta_{MP}(1 - \delta_{ID}V_{ID})$$

$$V_{ID} = 1 - \delta_{MP} + \delta_{MP}\delta_{ID}V_{ID}$$

$$V_{ID} - \delta_{MP}\delta_{ID}V_{ID} = 1 - \delta_{MP}$$

$$V_{ID}(1 - \delta_{MP}\delta_{ID}) = 1 - \delta_{MP}$$

$$V_{ID} = \frac{(1 - \delta_{MP})}{(1 - \delta_{MP}\delta_{ID})}$$

Given this value for V_{ID}, we can now determine payoffs for both players by plugging the value back into Table 2. However, the only value we need to calculate is the bottom-right cell corresponding to the ID's payoff (the ordinal price) in the odd period. This is because we know that in any arbitrary odd period, including the very first period, the ID will accept no less than its discounted continuation value, and so the MP, knowing this, will offer the ID that amount and the ID will accept the offer, ending the game. Therefore, the solution to this game results in the ID receiving an ordinal price of:

$$\mathrm{P}^* = \delta_{ID}\mathrm{V}_{ID} = \frac{\delta_{ID}(1 - \delta_{MP})}{(1 - \delta_{MP}\delta_{ID})} \in [0,1]$$

As seen in Rubinstein (1982), this is a unique solution. The solution given above is classified as a stationary solution, meaning that the strategies that the player adopt are static, i.e. they are the same in each round. It can be shown that even when this restriction is lifted, there are no additional solutions to the game (Spaniel, 2014).

In the next two sections of this chapter, I will discuss the predictions that can be derived from this model, and then discuss how elements of risk and uncertainty factor into the RBM.

Time Preference and Outside Options

The main implication from the solution to the RBM concerns the relationship between the discount factor of each player and the equilibrium ordinal price. The presence of a unique equilibrium solution to the RBM game means that it is possible to analyze how this equilibrium ordinal price changes as the players' discount factors change. By taking the derivatives of P* with respect to each discount factor, we obtain the following results (See Appendix A for derivation):

$$\frac{\partial P^*}{\partial \delta_{MP}} < 0 \ (when\ \delta_{ID} \neq 1)$$

$$\frac{\partial P^*}{\partial \delta_{ID}} > 0 \ (when\ \delta_{MP} \neq 1)$$

In both cases, if the opposing discount factor is exactly equal to 1, meaning that there is no time preference whatsoever, then the comparative static is 0. However, it is reasonable to assume that this is not the case since both agents in this context operate within modern financial markets with non-zero interest rates. A lower discount value means that the player values a quicker agreement more than a player with a higher discount value, or in other words is more impatient to make a deal. The negative sign on $\frac{\partial P^*}{\partial \delta_{MP}}$ indicates that as the MP gets more impatient to achieve a transaction, the price they will pay rises. Correspondingly, the positive sign on $\frac{\partial P^*}{\partial \delta_{ID}}$ indicates that as the irrigation district becomes more impatient to make a deal, the price they receive for the water right decreases.[9] These results make intuitive sense.

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[9] It is interesting to note that in the RBM, although the game itself is not symmetric (because a first-mover advantage usually exists), the result of the game is still symmetric (in terms of comparative statics).

The game is set up with the ID and the MP having different discount factors. The explanation for both discount factors not being equal to one is driven by the idea of time preference as discussed earlier. Colloquially, this can be interpreted as the level of ‘desperation’ on the part of a party to achieve a transaction, so it is natural to think that the two parties would not have identical discount factors/time preferences. The time preference of each player is a function of multiple parameters. First, focusing on the Municipal Provider, there are several predominant and measurable factors expected to influence time preference: They are the population of the MP’s service area and the per-capita water usage of that population, which together produce total urban demand for water. In the western United States, urban populations have been growing rapidly in recent years (U.S. Census Bureau, 2013), putting pressure on utilities to keep pace. The other part of the equation is the amount of water used per-capita. Although water use is particularly high in the West compared to other regions due to the climate, there is evidence to suggest that per-capita residential water use peaked around 10-15 years ago and has been very gradually decreasing. Additionally, municipal and industrial use per-capita has also levelled out in recent decades (Donnelly & Cooley, 2015). Another factor is the current surplus of supply that the Municipal Provider holds. If the MP previously invested in bolstering their supply of water rights, then the effect of increasing urban water demand on time preference may be delayed.

For the ID, it is not immediately clear what would specifically affect time preference, as opposed to the continuation value. One possibility is that if a farmer is close to experiencing external factors such as retirement that would prevent them from continuing to produce, then they would likely be more ‘desperate’ to sell quickly so that their rights do not sit unproductive for any amount of time. However, this factor, and other personal characteristics are not feasible to test with any available data, and so are not discussed further here.

Separate to the idea of time preference, the theoretical continuation values for each player bring up some interesting scenarios. Leaving the solution of the RBM as $p^*=\delta_{ID}V_{ID}$, we can easily see that $\frac{\partial P^*}{\partial V_{ID}} > 0$. Solving for $\frac{\partial P^*}{\partial V_{MP}}$ is not as straightforward, because the continuation value of the player that makes offers in odd-rounds (MP) is not explicitly modeled in the RBM. However, we can solve for this comparative static indirectly by using the fact that V_{MP} is implicitly stated when we consider that the ID had to offer at least $\delta_{MP}(1-\delta_{ID}V_{ID})$ in the even round to get the MP to accept, which, following previous logic, is the continuation value of the MP discounted by one round. This allows us to derive an expression for V_{MP} in terms of V_{ID} and derive the desired comparative static (this process is shown in Appendix B):

$$\frac{\partial P^*}{\partial V_{ID}} > 0 \qquad \frac{\partial P^*}{\partial V_{MP}} < 0$$

As with time preference, we can think about factors that would influence the continuation values of each player. These factors essentially correspond to BATNAs. Classical production theory suggests that if the price of the output being produced by an agricultural operation rises, then the marginal value of each unit of irrigation water will rise, given i) ceteris paribus and ii) the absence of any technological relationships between the inputs that alter the mix of inputs allocated to the production process (Beattie, Taylor, & Watts, 2009). In this case, the ID will place a greater value on the water right for agricultural use and will have a higher minimum price that they would be willing to accept because the alternative option of not selling the water right is now more attractive. Of course, maintaining ceteris paribus with respect to macroeconomic parameters in the long run is only possible in the (relative) short-run. Over a longer time-frame, agricultural producers consider their expectations about long-term profitability of their crop. Examples of factors which influence farmer expectations are subsidy programs such as the Farm Bill, which significantly affect the profit margins of farmers. A change or end to such programs could possibly affect the decision to continue to farm at the extensive margin, itself a decision that will certainly affect the market for water when considering many farmers in a basin/aquifer.

The other possible BATNA that could affect continuation values is the presence of other potential bargaining partners, which is applicable to both the ID and the MP. If either party possesses the option to buy from/sell to other players, then this creates a type of bargaining power, such as described and analyzed in Emerick (2007), where the disagreement payoff is the equivalent to the continuation value in the RBM. An additional outside option for the MP specifically is to increase its water supply from an alternative source such as recycled or manufactured water instead of through purchasing/leasing water rights. Finally, the ID could simply choose to continue to farm and postpone the sale/lease of water rights if it feels that the current appreciation rate of their water rights exceeds their discount rate.

Risk and Risk-Preferences

In the previous chapter, the element of risk and how the value of a paper water right can be affected by risk were discussed. Climate variability, and thus water right yield variability, is expected to rise over time, making this an increasingly relevant dimension to explore. Both anecdotally and from intuition, we know that urban water providers tend to be risk-averse, facing demand their customer base to deliver a certain amount of water, and face severe social and legal consequences if they do not. A well-cited example of this is the case of a recall election of city council members in Tucson, Arizona, where council members voted to increase water rates in response to insufficient water supply to meet demand. Public reaction was extremely negative and all four members were either voted out or resigned (Gelt et al., 1998). Farmers, on the other hand, as private business owners, reap the direct financial consequences of their water decisions. For this reason, we typically think of the municipal provider as relatively more risk-averse than agricultural producers. Therefore, in our bilateral model of the Irrigation District and the Municipal Provider, we would expect the two players to respond differently to risk, which may then alter the outcome of a bargaining game.

In the basic RBM, it is implicitly assumed that either i) payoffs have no risk, or ii) players are risk neutral. In the case of water rights markets, both statements are false. In addition to this, the economics literature discusses risk-aversion and time preference as interdependent, so that beliefs about risk may affect time preference (Anderhub et al., 2001). Since the present is known but the future contains risk, certain types of risk may create behavior that is biased towards the present in excess of any initial time preferences. There is some evidence in the literature where, as the risk associated with a payoff increases, a player's time preference changes (Andreoni & Sprenger, 2012).

In the classical bargaining literature, risk-aversion (relative to the other player) is a weakness in negotiations that leads to a worse outcome (e.g. Roth, 1985). However, in the last decade or so, theoretical literature shows that under certain circumstances, a risk-averse player may increase their payoff when there exists a risk associated with a payoff compared to when there is no such risk (Kohlscheen & O'Connell, 2008; White, 2008). In such cases, risk-aversion would conversely be considered as a strength in bargaining. In this thesis, I will focus on the characterization of risk in the RBM from White (2008). In her analysis, White took the basic RBM where one player is risk-averse and the other is risk neutral under two types of payoff risk, additive and multiplicative[10], and found conditions in each for which introducing risk into players' payoffs increases the receipts of the risk-averse player. For the case of the value of a paper water right, an additive treatment of risk is appropriate as the presence of drought conditions may cause a decline in the actual water yielded from a right. In the additive case, two conditions that are both sufficient for the risk-averse player to increase receipts when risk is introduced are:

i. *The risk-averse player exhibits non-increasing absolute risk aversion*
ii. *$U''' \geq 0$ and $\delta \leq 1$, with at least one inequality strict, where U is the utility function*

White summarizes these two conditions by noting that "additive risk will lead to an increase in receipts if risk aversion does not increase too quickly" (White, 2008). White also discusses a case where if the other player is characterized by pure fixed costs of bargaining,[11] then the risk-averse player exhibiting strict decreasing absolute risk aversion is a necessary and sufficient condition for increasing receipts of a risky payoff. However, even though we typically think of the ID as being less impatient than the MP, it is unlikely that they exhibit pure fixed costs of bargaining.

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[10] Additive risk is defined where an agreement results in a payoff of $x + z$, where x is the expected payoff and F(z) is independent of x. Multiplicative risk, on the other hand, is defined where an agreement results in a payoff of $x(1+z)$, where x is the expected payoff and z has a mean value of zero.

[11] "Pure fixed costs" typically refers to a case where a player does not have any time preference (δ=1), but there is some fixed cost associated with participation in each round of bargaining.

The only major parameter directly embedded in the RBM is the discount factor (δ), which represents time-preference. Thus, in the absence of altering the RBM to explicitly include risk, which is beyond the scope of this thesis, changes in the risk associated with the yield of a water right are incorporated to affect the ordinal transaction price through the time preference parameter. Following this idea, we can think of the Municipal Provider's time preference parameter (δ_{MP}) as a function of two exogenous factors:

$$\delta_{MP} = f(population\ growth, water\ yield\ risk)$$

Recalling that the expected effect of an increase in δ_{MP} on P* is negative, we can summarize White's predictions in the context of comparative statics for our model (denoting risk of water right yield as σ_w:

$$If\ \geq 1\ of\ White's\ conditions\ hold\colon \frac{\partial \delta_{MP}}{\partial \sigma_w} > 0, \quad \rightarrow\rightarrow\rightarrow \quad \frac{\partial P^*}{\partial \sigma_w} < 0$$

$$If\ White's\ conditions\ do\ not\ hold\colon \frac{\partial \delta_{MP}}{\partial \sigma_w} < 0, \quad \rightarrow\rightarrow\rightarrow \quad \frac{\partial P^*}{\partial \sigma_w} > 0$$

In the final section of this chapter, I will discuss which of the comparative statics derived during this chapter are feasible and/or most relevant to empirically test.

Testable and Untestable Predictions

Over the course of this chapter, I have derived five comparative statics for the outcome of the RBM when adapted for bilateral water right negotiations between an agricultural seller and municipal buyer. These are summarized in Table 3.

Recalling the previous section on time preference and outside options, it is difficult to think about potential proxies for the time preference of the Irrigation District, even if data was not a constraint. So $\frac{\partial P^*}{\partial \delta_{ID}}$ is not a testable prediction. Additionally, I am generally more

Table 3: Summary of Theoretical Predictions

Description	**Formula**	**Expected Sign**
Time preference of MP	$\frac{\partial P^*}{\partial \delta_{MP}}$	Negative (-)
Time Preference of ID	$\frac{\partial P^*}{\partial \delta_{ID}}$	Positive (+)
Outside Options of MP	$\frac{\partial P^*}{\partial V_{MP}}$	Negative (-)
Outside Option of ID	$\frac{\partial P^*}{\partial V_{MP}}$	Positive (+)
Risk (Variance) in Water Source Yield	$\frac{\partial P^*}{\partial \sigma_w}$	Ambiguous (?)

interested in the comparative statics relating to the Municipal Provider, because they are more exposed to risk associated with water right variability, and their outside options are more interesting than that of the Irrigation District, which is often just to continue using water to grow crops. Based on these considerations, the three comparative statics relating to the MP will be the focus of the econometric analysis in the next chapter, and are listed in Table 4.

Table 4: Tested Theoretical Predictions

Prediction #	Description	Formula	Expected Sign
1	Time preference of MP	$\frac{\partial P^*}{\partial \delta_{MP}}$	Negative (-)
2	Outside Options of MP	$\frac{\partial P^*}{\partial V_{MP}}$	Negative (-)
3	Water Right Yield Risk	$\frac{\partial P^*}{\partial \sigma_w}$	Ambiguous (?)

Chapter 4: Empirical Data and Variables

Previous Empirical Applications

Previous studies that have empirically analyzed water rights markets are not extensive. This is because easily accessible data on water transactions is sparse, which is the case for a few reasons: Firstly, markets are often not operated by any centralized entity. Transactions are often conducted informally, or markets exist on a local scale. Secondly, although state laws require legal proceedings to change the place and/or purpose of use of water rights, there is no requirement to disclose prices associated with transactions. Finally, Individuals and entities are often reluctant to disclose information regarding sale prices of water rights, as price information is valuable and a competitive advantage to those who have such information. The only sources of data encompassing multiple transactions are private water consulting companies that collect data to be used on behalf of their clients and sold as a commodity.

Nevertheless, some empirical analyses of market outcomes have been conducted, although none of them address time preference and risk directly. Colby et al. (1993) analyzed transactions from the 1980s in the Gila-San Francisco Basin of New Mexico using a linear model, and found that the priority date of the water right was a significant determinant of sale prices, and that the price-quantity relationship was consistent with traditional theory.

Brookshire et al. (2004) studied three distinct regional water markets from 1990-2001: The Central Arizona Project (CAP) in Arizona, The Big-Thompson Project (CBT) in Colorado, and the Middle Rio Grande Conservancy District in New Mexico, to determine differences in the three markets and to analyze price trends over time. These specific markets were chosen partly because they had sufficient transaction volume to analyze given the timeframe of data available. A simultaneous equations approach was used to estimate price and quantity equations. In the first equation, price is regressed on market, and buyer type while adjusting for population, income per capita, and weather conditions using the Palmer Drought Severity Index (PDSI). In the second equation, quantity of water transferred was regressed on price and various agricultural and land indicators. In the first equation, rising populations and income were positively associated with water prices. If the previous year was relatively wet, the price of water transacted decreased. Initial assumptions that municipal buyers have a higher marginal value for water than other buyers were confirmed. Consistent with theoretical assumptions, the CBT, which had the lowest transaction costs and most homogeneous water, had the highest trading volume and the highest price. On the flip side, the CAP suffers from high transaction costs, causing stymied market activity. In the quantity equation, and inverse relationship was found with price and the value of agricultural production, and as land prices increased, so did the amount of water transacted. Prices generally rose during the study time frame, indicating that the markets were adjusting the price of water towards its true value (2004).

Brown (2006) and Brewer et al. (2008) analyzed data from all western states. Brown found that for the western U.S. the number of leases, but not sales, have been increasing over time, and highlighted the high variability of prices between different states, citing wildly differing water laws and local market conditions. A simple regression was also run that found that municipal and environmental buyers of water paid a significantly higher price for water rights than agricultural buyers, with the magnitude being higher for the municipal group (2006). Brewer et al. came to similar conclusions regarding variation in prices, found that the number of ag-to-urban transactions was increasing compared to ag-to-ag ones, and that leases were trending from short-term contracts to longer ones (2008).

Emerick's (2007) work has already been mentioned a couple of times in previous chapters. The market power climate that water rights transactions occur in can fall on a spectrum anywhere from buyer monopoly to seller monopsony, and in many cases, are bilateral monopolies. The market power derived from these situations fall under the scope of outside options that were discussed earlier. Emerick found some moderate support for the hypothesis that market power affects the transaction price of transactions. Another master's thesis by Basta (2010) on urban water supply reliability looked at the determinants of market prices in markets that contained municipalities buying and/or leasing water for urban supply. Eight separate models were run for eight regional water markets in Colorado, New Mexico, Nevada, and Texas. Significant parameter signs were not always consistent across all markets, but it was generally the case that house prices were positively correlated with water prices, and both transaction frequency and the Standard Precipitation Index (SPI) were negatively correlated with prices. Unlike some of the previous literature, in which quantity transacted was shown to be negatively correlated with price, in Basta's models, this is not always the case: A market for the Front Range in Colorado exhibited a significant positive relationship, and in a few other cases, was positive but insignificant (2010).

A couple of papers have looked at the effect of climate variables on transactions. Pullen and Colby (2008) utilize the Standard Precipitation Index (SPI) as an explanatory variable, and find that negotiated prices are higher during drier years. Jones and Colby (2010) focused on environmental water transactions, specifically where water rights were purchased or leased for non-consumptive uses. The authors hypothesized that prices for these transactions vary based on weather and climate conditions at the appropriate scale, both due to the actual effects of these factors and because of perceptions about the effects of current climate trends. Econometric models were used to test for the effect of temperature and precipitation variables on transaction prices in four states, and found that both temperature and precipitation matter in some cases.

The most recent literature that analyzes water rights market data focuses on the decision to buy or lease water. Hansen et al. conducted a novel analysis using a maximum likelihood logit model to explain whether a buyer will choose to lease water or buy a water right permanently (2014). In addition to other relevant variables from previous literature, Hansen et al. also include a variable called “ag production”, which is an “indexed variable indicating percentage deviation from the state’s average annual value of production per acre over the study period” (2014). When the seller of the water right was an agricultural producer, a higher “ag production” value was correlated with a higher probability that the water right would be sold rather than leased. Their other results generally agree with previous conclusions by Brewer et al. (2008) that the market is trending towards higher lease activity rather than sales over time, although variability is still high between states. Meanwhile, Emerick and Lueck (2015) also distinguish between short-term and long-term lease contracts and use an ordered probit model to test the hypothesis that a longer contract duration (and a sale at the extreme) is more likely when “specific investments in infrastructure are required for conveyance” (2015). They also find that municipal buyers use longer-term contracts to reduce risk when it is initially high.

Data and Variables

When thinking about the population of transactions, of most interest for this analysis are transactions with agricultural users as sellers, and urban users as buyers. These types of transactions do account for the lion's share of entries in the available data, but there are other parties that engage in water transaction.[12] The other main buyers of water rights are environmental interests, which usually take the form of non-profit organizations or government agencies. The presence of transactions from agricultural producers to environmental buyers suggests that the marginal value of use for environmental water can be higher than for irrigation. However, in some cases, court rulings and regulations place pressure on municipal or industrial users of water to sell/lease water to bolster environmental flows. These transactions do appear in some transaction data, but prices are often set by administrative agencies, and these are referred to as "administrative transactions".

I will now give a brief overview of the three western markets that were chosen for this analysis. These markets were chosen because i) they are centered around large urban areas with agricultural production in the surrounding region, ii) they are all located in states that primarily use prior appropriation to allocate water rights, unlike a few states in the West that combine prior appropriation with riparian systems (e.g. California and Texas), and iii) they have sufficient market activity to analyze econometrically.

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[12] Here I am discussing the population of transactions reflected in accessible data, which does not always represent all actual transactions. Transfers that occur within irrigation districts are common in the West. However, if a water right is not being moved from the irrigation district, and the use of water remains in agriculture, then the legal requirements for changes in water rights do not apply. These local, within-district transfers still involve water being moved from a lower-valued use to a higher one, but will not usually be included in water transactions data.

Front Range, Colorado

Colorado has perhaps the most active water markets in the West. Almost all the major metropolitan areas in Colorado are located on the Front Range, including, but not limited to Denver, Fort Collins, Colorado Springs, and Pueblo. Therefore, the large majority of Colorado transactions occur with buyers in this area. A large proportion of the water that supplies the state comes from the headwaters of the Colorado River on the West Slope. The Arkansas River, which eventually drains to the Mississippi River, also provides water to the southern portion of the Front Range. Various conveyance structures were built in the 20th century largely for diverting water from the West Slope to the Front Range, most notably associated with the C-BT Project and the Fryingpan Arkansas Project. Water rights transactions in Colorado must be approved by a judge in Water Court, who must ensure that the transaction includes conditions necessary to prevent injury to other water rights holders (Hobbs Jr, G. J., 2015).

Middle Rio Grande, New Mexico

Two of New Mexico’s biggest Metropolitan Statistical Areas (MSAs) are the Albuquerque MSA and the Santa Fe MSA, located along the Rio Grande River. As a result, the large majority of New Mexico transaction activity occurs in this area. Interestingly, the priority dates of water rights in New Mexico are relatively homogenous, with 1907 being a particularly common priority date. Any rights with a priority date before/after 1907 is regarded as ‘senior’ or ‘junior’ respectively (Brookshire et al., 2004). This homogeneity lends itself to formation of a market for water rights. However, the legal process of transferring water rights still suffers from delays and uncertainties (2004).

Reno, Nevada

Nevada has relatively few urban centers, Reno and Las Vegas being the only two of note here. However, the Las Vegas market is not analyzed in this thesis. During the mid 20th century, Las Vegas bought up the water rights of most agricultural operations in the surrounding in-state region, so there is no longer much scope for ag-urban transactions. The water market in the Reno-Sparks Metro Area derives its water mainly from both the Truckee and Carson Rivers, which are supplied by snowmelt from the Sierra Nevada Mountain Range, straddling the California/Nevada border. Most of Nevada is part of the internally-draining "Great Basin", and receives fewer than 10 inches of precipitation each year, making it the driest state in the U.S. (Wilds, 2010). Although Reno-Sparks municipal providers are the only large urban buyers in the market, an environmental non-profit, *Great Basin Land and Water*, has been a part of numerous transactions in the Reno market in recent years.

Two separate datasets are utilized in the empirical analysis; one well-known and previously used, the other novel. The first of these is obtained from *The Water Strategist*[13] (TWS), a now-defunct publication by *Stratecon Inc.* that was published monthly from 1987-2010. At the beginning of each issue, water transactions that had occurred in one of 13 western states since the last issue were listed. Various subsets of this data have been used in past empirical work. In fact, almost all relevant literature cited in the previous section uses this dataset. The second dataset, which will be referred to as *AcreValue*, comes from a website of the same name. AcreValue is an online, GIS-based platform run by *Granular Inc*. that provides agricultural land information such as historical use and sale prices. *Granular Inc*. recently announced a partnership with *WestWater Research Inc*., a private company that collects data in

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[13] Previously known as the *Water Intelligence Monthly*.

much the same way as was done for TWS, that would allow it to add data on water rights transactions to its platform. Data was collected from AcreValue by a graduate student at the University of Arizona. Transaction data begins in 2012 and at the time of writing includes transactions up to 2017. The two datasets contain slightly differing information, although the basic variables are the same. For illustration, one example entry from each dataset is described here:

The Water Strategist, Example Entry

Reported in *TWS*, January 2007 issue, A transaction in 2006 occurred where an unnamed irrigator permanently sold rights totaling 13.8 acre-feet to the Town of Lyons for a 2016-adjusted price of $20,604.09/acre-foot.

AcreValue, example entry

In 2012, a transaction occurred concerning a buyer located in Loveland, Larimer County, Colorado. The transaction was a permanent sale of surface water rights. 4.9 acre-feet of rights were bought for a 2016-adjusted price of $12,000.45/acre-foot.

For both datasets, data cleaning and selection narrowed down the set of useable observations. For some transactions, no information on price and/or quantity is available, and so such observations were discarded. This problem occurs more frequently in *TWS* data than *AcreValue* data. In addition, some transactions recorded in *TWS* include a transfer of both water and other assets (e.g. land rights). If the value ascribed to the water rights cannot be separated from that of other transacted assets, then the observation is also discarded.

Some observed transactions are of a type that is not relevant to the current analysis: Firstly, some observations in the data are exchanges, which occurs when an upstream user diverts water upstream from where it would usually be diverted, under the condition that they will replace the water "at the time, place, quantity, and suitable quality the downstream diverter enjoyed before the exchange" (Hobbs, 2015). Secondly, there exist transactions of water rights where municipal, industrial, or agricultural water users are mandated by government entities to sell/lease some of their water rights to these entities. Such transactions are usually conducted to protect the habitat of endangered species, and the prices paid for these rights are often substantially below typical market value. For these reasons, these transactions are not included in the analysis.

For creating some predictor and control variables, regions with more than one urban market area, the general location of the buyer needed to be established, so that an assertion regarding which market the transaction falls under could be determined. *AcreValue* data includes the county of the buyer (and in some cases, coordinates too). However, in *TWS* data, sometime either the buyer location data was missing, or it was too vague to assign a location. In this case, the original *TWS* publication was referenced in an attempt to fill in this information. In cases where this could not be done, the observation was deleted. Table 5 shows the potential 'zones' that water rights buyers could be assigned.

A list of the variables used in the main model and alternative models and their definitions can be seen in Table 6, and selected descriptive statistics in Table 7. Additionally, a few descriptive statistics by zone for Colorado and New Mexico can be seen in Tables 8 and 9. As discussed previously, feasible transaction markets exist based on the physical and legal conveyance facilities in a region, including groundwater aquifers. Thus, the ideal level for aggregating/disaggregating predictor and

Table 5: Urban 'Zones' by State

State	**Colorado (CO)**	**New Mexico (NM)**	**Nevada (NV)**
Zone 1	Boulder (BDR)	Albuquerque (ABQ)	Reno (RNO)
Zone 2	Colorado Springs (CS)	Santa Fe (SF)	
Zone 3	Denver (DEN)		
Zone 4	North Front Range (NFR)		
Zone 5	Pueblo (PBO)		

control variables is the transaction region. This is often difficult to do because the geography of conveyance infrastructure and aquifers often does not follow defined political boundaries. In the case of each variable where this is a concern, the best effort was made to dis(aggregate) the variable appropriately using knowledge of water markets and other salient factors.

Dependent Variable

The dependent variable PRICE was calculated by taking the price paid per acre-foot and adjusting to 2016 USD using a Consumer Price Index (CPI) calculator from the Bureau of Labor Statistics (BLS). Histograms of PRICE for each state are shown in figures 3, 4, and 5. We can see that in all three states, PRICE has a significant positive skew, with New Mexico having the strongest skew. In Colorado and New Mexico, a portion of this effect can be explained by the fact that the data contains both leases and sales: Lease prices are significantly lower than prices of sales. This point is accentuated by the fact that New Mexico has a higher proportion of transactions that are leases compared to Colorado, and as such, PRICE has a stronger positive skew in New Mexico. To adjust the dependent variable for the remaining skew not accounted for by the lease/sale effect, the natural log of PRICE, denoted LN_PRICE, was used in the analysis. Other econometric analysis has found that using the natural log of price usually gives better fit, most explicitly described in Basta (2010).

Table 6: Description of Variables

Variable	**Description**
Dependent Variable	
PRICE	Real price paid per acre-foot of water (2016 dollars)
Control Variables	
QUANTITY	Number of acre-feet transacted
D_LEASE	= 1 if the transaction was a lease, 0 otherwise
SPI_LX_SNOW	Standard Precipitation Index (12-month) for the climate division where the water source originates from, lagged X months
SPI_LX_URBAN	Standard Precipitation Index (12-month) for the climate division where the buyer is located, lagged X months
REAL_GDP_CAP	Real GDP per capita (2016 $) for the metro area where the buyer is located nearest to
POP	Population (000's) for the metro area where the buyer is located nearest to
ALFALFA	State alfalfa price (2016 $)
D_AV	= 1 if the observation comes from the AcreValue data, 0 otherwise
D_GROUND (*AcreValue* Only)	= 1 if groundwater was transacted, 0 otherwise
D_AG_URBAN (TWS ONLY)	= 1 if seller is ag and buyer is urban, 0 otherwise
Predictor Variables	
SPI_SNOW_VX	Variance of SPI_L0_SNOW in the last X years
SPI_URBAN_VX	Variance of SPI_L0_URBAN in the last X years
POP_5YR	5-year population growth (%) for the metro area where the buyer is located nearest to
ALFALFA_PROD	Alfalfa production (000’s tons) in the counties that have the conveyance facilities to sell water rights to urban

Table 7: Selected Descriptive Statistics

	Colorado			New Mexico			Nevada		
Variable	**Mean**	**Median**	**St. Dev**	**Mean**	**Median**	**St. Dev**	**Mean**	**Median**	**St. Dev**
PRICE	17,262	17,721	12,395	3,860	101	5,260	6,582	4,042	8,500
QUANTITY	402	14	2,025	1,029	66	5,721	172	19	468
D_LEASE	0.18	0.00	0.38	0.51	1.00	0.50	[redacted]	[redacted]	[redacted]
SPI_L12_SNOW	0.03	0.38	0.82	-0.16	0.28	0.80	-0.37	-0.01	0.84
SPI_L12_URBAN	0.15	0.16	1.02	-0.28	0.04	0.81	-0.37	-0.65	0.80
SPI_SNOW_V5	0.56	0.75	0.26	0.39	0.39	0.14	0.67	0.53	0.30
SPI_SNOW_v10	0.60	0.53	0.13	0.56	0.54	0.09	0.70	0.74	0.19
REAL_GDP_CAP	40,101	35,475	10,498	42,302	40,733	2,901	47,410	45,090	4,236
POP	880	545	780	787	903	251	434	437	18
POP_5YR	9.17	9.74	2.78	3.90	3.02	2.81	5.33	4.10	2.65
ALFALFA	166.74	157.08	41.79	237.88	261.59	35.38	189.62	213.21	36.64
ALFALFA_PROD	867.78	862.20	182.30	168.79	176.80	49.46	191.49	197.10	54.23

Table 8: Descriptive Stats by Zone (Colorado)

	BDR (n = 65)		CS (n = 23)		DEN (n = 80)		NFR (n = 568)		PBO (n = 49)	
Variable	**Mean**	**St. Dev**	**Mean**	**St. Dev**	**Mean**	**St. Dev**	**Mean**	**St. Dev**	**Mean**	**St. Dev**
PRICE	18,469	11,574	3,785	4,916	7,765	11,261	20,503	11,049	974	5,028
QUANTITY	61	146	937	1,548	1,146	2,579	58	178	2,746	5,246
D_LEASE	0.09	0.29	0.52	0.51	0.48	0.50	0.05	0.23	0.98	0.14
SPI_SNOW_V5	0.58	0.25	0.49	0.31	0.57	0.26	0.55	0.26	0.64	0.29
POP_5YR	6.58	1.64	6.89	0.83	7.11	2.09	10.35	1.96	3.62	1.51
ALFALFA_PROD	938	137	464	135	856	147	905	151	567	78

Table 9: Descriptive Stats by Zone (New Mexico)

	ABQ (n = 62)		SF (n = 9)	
Variable	**Mean**	**St. Dev**	**Mean**	**St. Dev**
PRICE	4,140	5,347	1,931	4,398
QUANTITY	1,041	6,125	948	576
D_LEASE	0.47	0.50	0.78	0.44
SPI_SNOW_V5	0.39	0.13	0.41	0.20
POP_5YR	3.94	2.98	3.65	1.25
ALFALFA_PROD	185	26	56	6

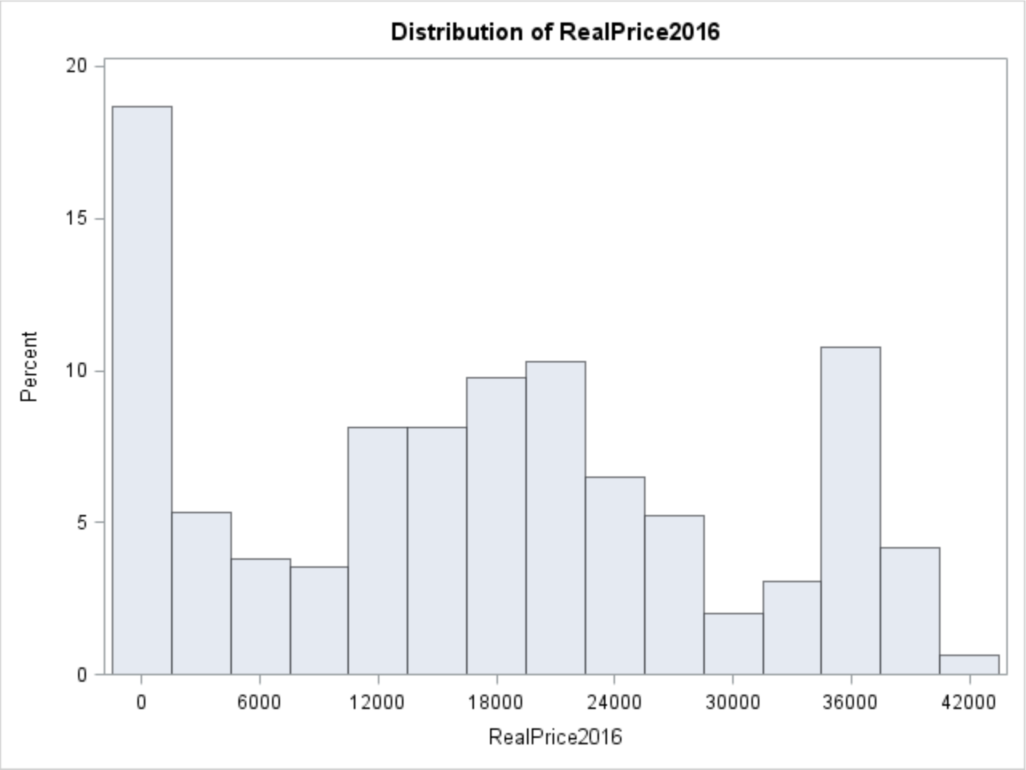

Figure 3: Distribution of Price, Colorado

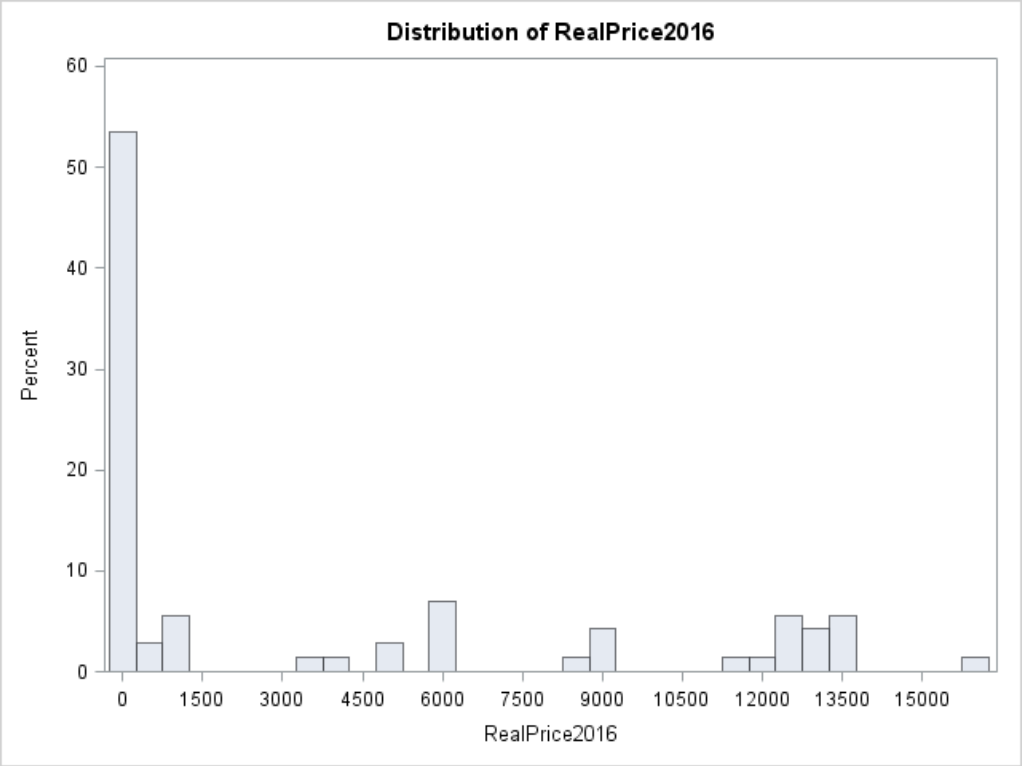

Figure 4: Distribution of Price, New Mexico

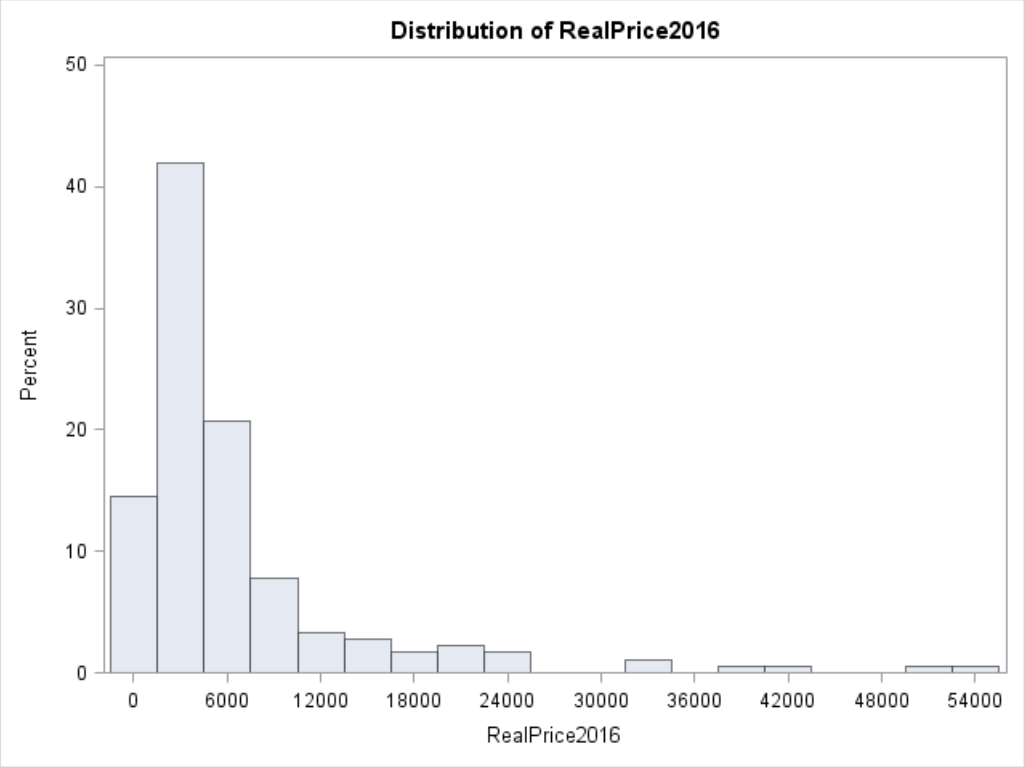

Figure 5: Distribution of Price, Nevada

Control Variables

Control variables included in the model account for factors that are not present in the theoretical model. Nonetheless, some of them also have potentially interesting interpretations. Quantity is expected to have a significant and negative effect in all models as per fundamental economic theory. Like with price, outliers are common for the quantity variable, so the natural log of quantity was used in all models, denoted LN_QUANTITY. D_LEASE is also expected to have a significant negative effect on price outcomes. Emerick (2007) chose reconcile differences between leases and sales by discounting sales with a factor of 0.05. While this option was also considered, it was decided that a simple dummy was a preferable choice.

SPI_LX_SNOW and SPI_LX_URBAN represent multiple versions of the 12-month Standard Precipitation Index (SPI), which provides a normalized value for the level of precipitation over the previous 12 months. Negative SPI values indicate drought conditions, whereas positive values indicate abnormal wetness (compared to historical precipitation levels). Although there are other measures that could have been chosen to measure precipitation, the Palmer Drought Severity Index (PDSI) being one, the SPI was chosen because it is more suitable for comparing values across regions with different climates than the PDSI (NCAR, n.d.). The 'X' in each variable refers to the number of months that the SPI was lagged. Lags of 0, 12, and 24 months were investigated in preliminary analysis. SPI_LX_SNOW denotes the SPI value for the climate division where the water that supplies the market originates from, whereas SPI_LX_URBAN denotes the SPI value for the climate division in which the buyers are located. I would hypothesize that the snow-based SPI value is more relevant for water markets since the precipitation in these regions is more directly related to eventual flows downstream from snowmelt. However, I think it is useful to also include an urban precipitation indicator, as this is what the municipal water manager observes on a daily basis, and it is not implausible to think that this may affect decision-making. Maps of climate divisions are shown below for Colorado, New Mexico, Nevada. California is also shown as it contains the snow SPI climate division for Nevada In Colorado, all surface water that ends up on the Front Range originates from the Rocky Mountain area around the headwaters of the Colorado River, so division 5 is chosen for the snow SPI, and division 4 is chosen for the urban SPI. The Middle Rio Grande River that flows through the main urban markets in New Mexico originates in south-central Colorado, so Colorado climate division 5 is chosen to represent the snow SPI, and division 5 is used for buyers in the urban areas. Finally, water that flows through the Truckee-Carson Basin to the Reno metropolitan area originates from the Sierra Nevada Mountain Range on the California-

Nevada border, so division 3 in California is chosen for Nevada, and division 1 is chosen for the urban Reno area.

The variable REAL_GDP_CAP, which measures the overall ‘wealth’ of a municipality, is used in logarithmic form like PRICE and QUANTITY due to an expectation for the effect of a higher GDP/capita to decrease as the variable increases, and to improve the fit of the variable. The population variable POP has an interesting interpretation somewhat related to bargaining strength: I hypothesize that a larger city will tend to have had more experience buying water rights, and that this experience in bargaining will allow them to avail a better (lower) price in negotiations than if they did not have this experience. Cities with larger populations can also benefit from a quantity discount since they are buying rights for a larger population, but the

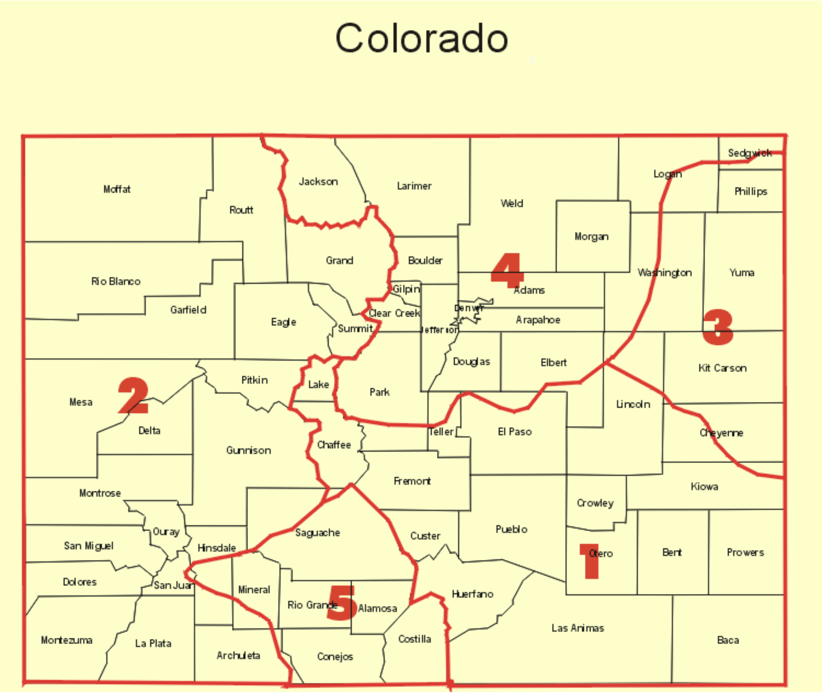

Figure 6: Climate Divisions of Colorado

Figure 7: Climate Divisions of New Mexico

Figure 8: Climate Divisions of Nevada

Figure 9: Climate Divisions of California

LN_QUANTITY variable is expected to absorb this effect. Population here is defined by the sum of population in the Metropolitan Statistical Areas (MSAs) for the largest cities in the relevant 'zone'.

The underlying motivation for water rights transactions is a gap between the MVP of water for different uses. Although the comparative statics relating to the Irrigation District in the theoretical model are not the primary focus here, if the price of crops grown by the ID become more profitable, then the ID has a stronger outside option, which I would expect to lead to a higher transaction price. Alfalfa is a relatively low-value crop that is water intensive. These two factors mean that the marginal value of product of alfalfa is likely low, and farmers that cultivate alfalfa are the most likely to sell their water rights, all other things equal. Therefore, the variable ALFALFA is included and is expected to have a positive sign.

Predictor Variables

The variables discussed below are the proxies that I use to test the hypotheses developed in the previous chapter. Figure 10 graphically shows how the three parameters being considered affect the transaction price. For each prediction, it is useful to contrast the ideal proxy to the one used.

For time preference, an urban buyer would be more impatient to obtain new water rights if urban water demand was growing at a faster rate, meaning that full supply capacity will be reached sooner. Of course, this can be delayed/offset if the buyer had previously invested in additional supplies, so current spare capacity would be an ideal variable to have too.

For outside options, there are two main potential alternatives: The first is the outside options for water rights. If there are more potential sellers that the buyer could feasibly engage with, then their outside options would be stronger. Secondly, if there are feasible alternative to obtaining water beyond purchases and leases, such as increasing effective supply through recycling water or through desalination, then the buyer's outside options would also be stronger.

Finally, for risk in yield from the water source, if the variance in supply available from the given water source is higher, then one would infer that there is more risk associated with the yield of a paper water right, given a fixed priority date.

SPI_SNOW_VX and SPI_URBAN_VX represent the variance of the SPI_L0_SNOW and SPI_L0_URBAN variables over the last X years. The value (actual yield) of a water right in each year is a function of both its seniority and the total amount of water available from the water source. These variables are proxies for the risk (variance) associated with the yield from the water source (prediction 3 from Table 4). From the discussion on risk in the previous chapter, the effect of increased risk in the payoff to the relatively risk-averse Municipal Provider is ambiguous and as shown by White (2008) depends on the risk preferences of the MP.

POP_5YR is the average yearly population growth rate of the relevant MSA over the previous five years. This is my proxy for the time preference of the MP (prediction 1 from Table 4). A higher population growth rate indicates that the MP will be more impatient to secure a transaction, and so I expect this variable to have a positive sign in price equations.

ALFALFA_PROD is the main measure of outside options for the Municipal Provider (prediction 2 from Table 4). Alfalfa was chosen as the primary crop to use because i) it has one of the lowest (if not the lowest) marginal value of water of any crop grown in the West, and so one can argue that it will usually be alfalfa farmers that sell or lease their rights and fallow their land before other farmers, and ii) alfalfa is a widely-grown crop in the study regions, so there is sufficient acreage in production to give a meaningful variable. Information on the extent to which this assertion is true is available, but not extensive. One program that contains significant fallowing activity is the System Conservation Pilot Program (SCPP). Data on fallowing agreements shows that indeed, the majority of fallowing agreements involve alfalfa hay and/or grass pastures, although there are a handful of agreements involving other field crops such as corn, wheat, and oats (UCRC, 2018). Nonetheless, acknowledging that alfalfa alone may be too narrow of a measure, I also use an alternate variable (for Colorado only) called *CROP*_ACRE. This variable is constructed as follows. I look at state agricultural data in the first and last years of my transaction data (2002 and 2016). Any field crop that is among the largest in the state (by acreage) for either year is selected. Then the acreage of each selected crop is summed to give *CROP_ACRE* for each year. Missing crop acreage data was a significant problem for implementing this methodology, and so it was only implemented for Colorado.

The more alfalfa (or other field crop) production that exists in the feasible transaction universe for a given provider, the more potential transaction partners. What exact areas define sellers that exist in the buyer's feasible transaction universe is not simple to determine in every case. For a seller to be in this universe, their water rights must be from a water source such that sufficient conveyance facilities exist to transport that water to the potential buyer's location. A qualitative analysis was performed for each zone to determine, at the county level, which sellers counted as viable transaction partners. This was done by considering hydrologic basins, location of physical infrastructure, and legal factors affecting what types of transfers are permissible. The result of this was a list of counties for each urban zone that together contained the potential ag sellers for buyers in that zone. Alfalfa production for these counties was then summed by year to create the ALFALFA_PROD variable. This process is described in more detail in Appendix C.

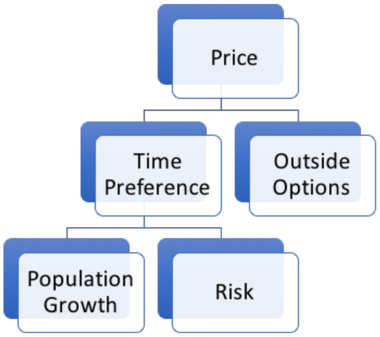

Figure 10: Flowchart of Parameters Affecting Transaction Price

Before moving into the econometric testing and modeling, it is illuminative to examine the univariate trends in key variables such as price and quantity, especially since data on water rights transactions is rare. Figures 11 and 12 display price and quantity trends respectively over time for each state. Note that the lines for New Mexico in these figures are broken because, due to transaction activity, there were no transactions reported in some years. Looking at Figure 11, it seems that prices reached a minimum as the recent financial crisis hit, although in Colorado prices had been gradually falling for a few years, whereas Nevada seemed to be hit a lot harder and more suddenly. Prices rebounded quickly in Colorado, but have struggled to do so in New Mexico and Nevada, which may be explained by how housing markets have rebounded in the time since the United States exited from recession. It is interesting that Colorado transactions appear as if they foreshadowed the eventual housing crash and started declining earlier, compared to Nevada. This price trend graphic provides a nice continuation to Brewer et al. (2004), showing that the increasingly-upward trend in average water prices did not continue unabated. Looking now at Figure 12, there is a clear difference between the first and second distinct time periods in the data. In the 2002-2009 period, there is a lot more variation in quantity, both within and between states. Conversely, in the last few years, corresponding to the 2012-2016 period, prices seem more homogeneous, and in the case of Colorado and New Mexico, the average size of transactions seems to have decreased.

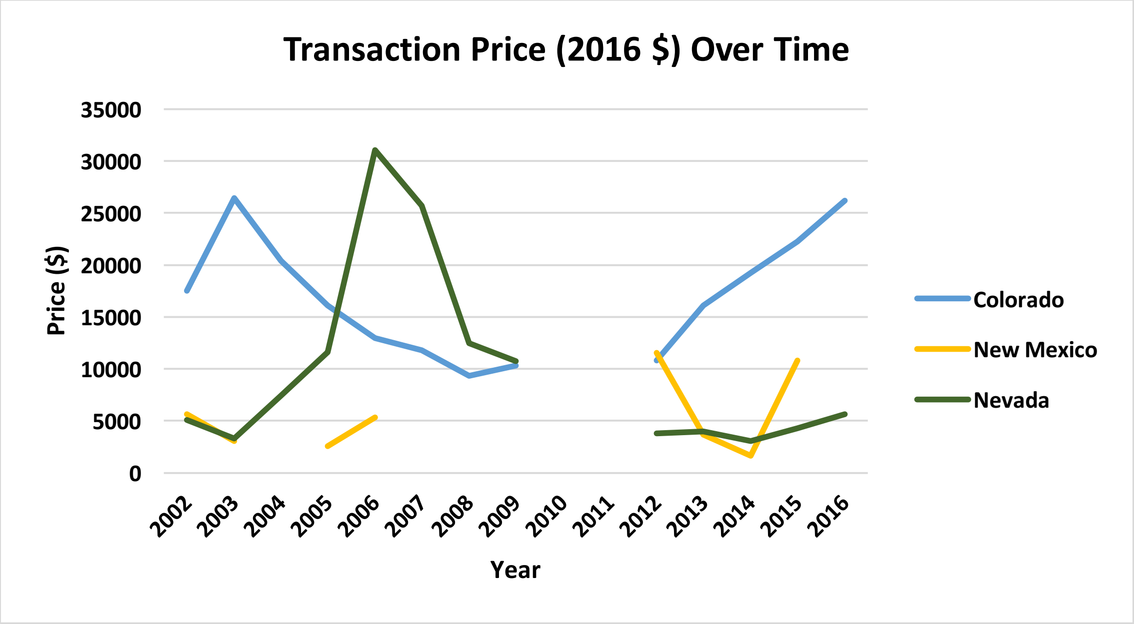

Figure 11: Average Transaction Prices over Time, Measured in 2016 $USD

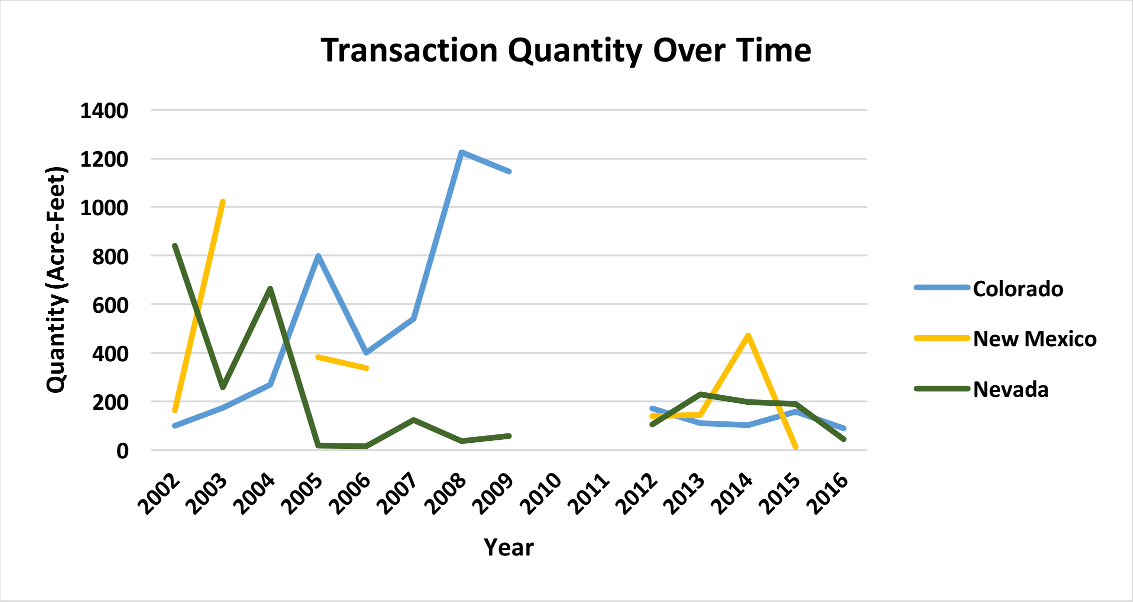

Figure 12: Average Transaction Quantities over Time, Measured in Acre-Feet

Chapter 5: Econometric Tests and Models

Tests & Models

Drawing from the theoretical model, the ordinal price of the ordinal transaction is a function of exogenous variables. My main analysis will econometrically estimate a linear equation with price of the transaction as the dependent variable. Since there are two datasets that are disjoint in time, the question of whether to run one joint model or separate models arises. The Chow Test provides a statistical indication as to whether two sets of data should be run as one joint regression or two separate ones by testing whether the coefficients in separate linear regressions are equal (Chow, 1960, Wooldridge, 2009). The Chow Test was run for each state, and the null hypothesis of equality of coefficients was rejected in each case, as might be expected. However, rather than running models separately for *TWS* and *AcreValue* data, the two datasets were combined for each state, which was done for two reasons. First, the data collection process for the *TWS* and *AcreValue* is very similar; both datasets are compiled by private firms that offer consulting services and the methodology is known to be similar. Second, *AcreValue* results sometimes struggled for significance, but in the combined results significance was much better. Results for both the Chow Tests and separate models can be found in Appendix D.

I will talk about two main potential econometric issues with implementing a linear price model, both of which are very common, and describe my approach to dealing with them. The first of these is heteroscedasticity, which refers to linear models where the residual terms in the equation have non-constant variance. One of the Gaussian assumptions that must be satisfied for the ordinary linear model to be a Best Linear Unbiased Estimator (BLUE) is for these residual terms to have constant variance, also known as ‘spherical errors’. The consequence of this is a loss of efficiency in the parameter estimates (Kennedy, 1992). To determine whether this assumption is violated, I run two diagnostic tests, White’s Test and the Breusch-Pagan Test, with homogeneity as the null hypothesis. The Breusch-Pagan Test is run on D_LEASE (if available) and D_AV, as it seems plausible that these two groups may be distinct and thus violate the assumption of homoscedasticity. Results of both tests are shown in Table 10. Colorado and New Mexico show strong signs of Heteroscedasticity in both tests, whereas in Nevada this does not seem to be an issue. In Nevada, there was only one observation that was a lease across the two data sources, so it was deleted, and thus there is no dummy for lease in the Breusch-Pagan Test. For Colorado and New Mexico, because the level of significance is similar in the White and Breusch-Pagan Tests, White’s Robust Standard Errors were used to deal with the heteroscedasticity.

Table 10: Results of Tests for Heteroscedasticity

State	Test	Variables	Pr > ChiSq	Reject H_0?
Colorado	White	Cross of all vars.	<.0001	YES
	Breusch-Pagan	D_LEASE, D_AV	<.0001	YES
New Mexico	White	Cross of all vars.	0.0428	YES
	Breusch-Pagan	D_LEASE, D_AV	0.0078	YES
Nevada	White	Cross of all vars.	0.8016	NO
	Breusch-Pagan	D_AV	0.3568	NO

The second roadblock to implementing the linear model is the potential endogeneity of the quantity variable. Typically, whenever price and quantity are in the same model, with one of them being the dependent variable, there is a suspicion that reverse causality exists, as economic intuition often concludes that price and quantity simultaneously influence each other. In my model, LN_QUANTITY is an explanatory variable, and to run the simple linear model, all explanatory variables must be exogenous to the model (i.e. they are not independent of the error term). If this is not the case, then the parameter estimates will be biased and inconsistent (Kennedy, 1992). Going back to the design of the theoretical model in the previous chapter, the fact that the quantity transacted between the seller and the buyer was assumed to be fixed based on the intuition from the cooperative Nash model and anecdotal evidence makes this question of endogeneity even more relevant. Endogeneity of LN_QUANTITY is tested using the Hausman-Wu Test, with the null hypothesis being that LN_QUANTITY is exogenous. If the null is rejected, then a Two Stage Least Squares (2SLS) model must be used instead of the linear one. One of the common difficulties with implementing the Hausman-Wu Test and the 2SLS is that finding good instrumental variables can be a challenge itself, as they must be a good predictor of quantity, but not have a causal relationship with price, except indirectly through quantity. A good starting place with my data is to look at climate-based variables, as we can be sure that they themselves are exogenous to the model (i.e. price and quantity themselves do not directly cause changes in climate). After some preliminary testing, it was found that for the Colorado and Nevada models, SPI_L0_SNOW fit the criteria for a good instrumental variable, and since SPI_L0_SNOW does not have any important economic meaning in this theoretical model it was used in the Hausman-Wu Test. For New Mexico, no suitable instrumental variable could be found with the specification used for Colorado and New Mexico. However, after some investigation, I found that SPI_URBAN_V5 was a suitable instrumental variable when taken out of the original specification. This means that it cannot be used in the main regression, but fortunately SPI_SNOW_V5 is, an arguably has a more intuitive economic interpretation. The results of the Hausman-Wu Test for each state is shown in Table 11. A more detailed summary of the two stages of the tests can be found in Appendix E. For all three models, the test failed to reject exogeneity. Obviously, the suitability of instrumental variables can be debated, but these results give some credence to the idea that there is a single, best quantity that is independent of the eventual price agreed upon.

Table 11: Results of Hausman-Wu Tests

State	Test	IV	p-value	Reject H_0?
Colorado	Hausman-Wu	SPI_L0_SNOW	0.9071	NO
New Mexico	Hausman-Wu	SPI_URBAN_V5	0.7940	NO
Nevada	Hausman-Wu	SPI_L0_SNOW	0.9030	NO

The results of the three linear models are shown in Table 12. Two models are shown for Colorado. (1) is the regular model using *ALFALFA_PROD*, and (2) is the alternative one that uses *CROP_ACRE*. I will first direct the discussion of results to those variables that are proxies for testing the predictions from the end of the previous chapter, and then comment on interesting estimates of control variables. Glancing at Table 12, it will be clear that the Nevada model is the weakest of the three, and sometimes exhibits results that are contradictory to the Colorado and New Mexico models. I suspect that this is due to the lack of variation in some explanatory variables stemming from the fact that there is only one large urban area in the Reno area, whereas in Colorado and New Mexico there are five and two respectively. This fact especially will affect the population and crop production variables, because these variables vary both in space and time, but because there is only one urban center in the Nevada model the space aspect of variation is taken away. Analysis of this issue was done via the coefficient of variation (COV), which is the ratio of the standard deviation and the mean of a sample, for the price variable, and variables that contain variation across zones. Results are shown in Appendix F. The coefficient of variation analysis shows mixed results: Although the COV of LN_PRICE is noticeably lower in Nevada than in Colorado and New Mexico, this is not the case for all independent variables. For example, for ALFALFA_PROD and POP_5YR, Nevada actually has a higher COV than Colorado. Unsurprisingly then, the Colorado and New Mexico models produce results that are more in line with a priori assumptions about water markets. POP_5YR has the expected positive sign in Colorado and New Mexico, and is strongly significant in Colorado, meaning that buyers in urban areas experiencing faster population growth pay more for water rights, although the relative effect is not large in magnitude.

The proxy for the outside options of the Municipal Provider, ALFALFA_PROD, does not have the expected sign in any of the models, but is insignificant in Colorado and Nevada, and only just significant in New Mexico. The significant result in New Mexico suggests that when there is more alfalfa production in the areas that an urban buyer could hypothetically purchase water rights from, they in fact pay slightly more for these rights. In addition, the *CROP_ACRE* variable in the second Colorado model has the same sign as ALFALFA_PROD, but is highly significant.

Similarly, this suggests that as the acreage of potentially fallow-able field crops increases, buyers are paying more for water.

Finally, the proxies for yield variability in water supply sources show a good amount of significance, but the results are not always consistent. In Colorado, SPI_SNOW_V5 has a significant positive effect on price, whereas SPI_URBAN_V5 has a significant negative effect. The snow-based version has more intuitive appeal, as discussed earlier, so I am inclined to place more weight on this result. SPI_SNOW_V5 is positive and significant for Colorado and New Mexico, indicating that when water supplies become more 'risky', urban buyers tend to pay a premium, which suggests that their relative risk-aversion is a disadvantage in bargaining. However, in Nevada, the opposite is true, and the relative risk-aversion is a 'strength' in bargaining. There are no simple and strong conclusions that can be made from these results, and one should be cautious not to attempt to do so. However, based on the work of White (2008) discussed in the previous chapter, where non-increasing absolute risk aversion is a sufficient condition for the risk-averse player to benefit from the presence of risk, we might be able to say that buyers in Colorado and New Mexico as a group are displaying this type of risk-aversion. Additionally, if it is the case that the Irrigation Districts have pure fixed costs of bargaining, then we can say that buyers in Colorado and New Mexico exhibit strict decreasing absolute risk aversion (DARA). For the most part, control variables in the models behave as expected. LN_QUANTITY is consistently negative and significant, indicating a quantity discount. The result from D_LEASE is expected but trivial. A positive sign on LN_REAL_GDP_CAP indicates that buyers in wealthier areas are willing to pay more for water rights.

POP is a measure of population in the metropolitan statistical area where the buyer is located. Although population growth is the main indicator of urban time preference, population

Table 12: Estimated Parameters from Price Models

	Dependent Variable: LN_PRICE			
Independent Variable	Colorado		New Mexico	Nevada
	(1)	(2)		
Intercept	__-11.79*__ (6.47)	-11.51 (9.34)	-63.01 (38.58)	__-106.40**__ (49.71)
LN_QUANTITY	__-0.17***__ (0.02)	__-0.17***__ (0.02)	__-0.22*__ (0.12)	__-0.14***__ (0.03)
D_LEASE	__-3.52***__ (0.12)	__-3.52***__ (0.20)	__-3.66***__ (0.43)	
SPI_SNOW_V5	__0.70***__ (0.22)	__0.59***__ (0.22)	__2.15**__ (0.92)	__-1.65*__ (0.84)
SPI_URBAN_V5	__-0.76***__ (0.24)	__-0.99***__ (0.25)		1.13 (0.87)
LN_REAL_GDP_CAP	__2.11***__ (0.64)	__2.11**__ (0.91)	__6.92*__ (3.64)	__9.91**__ (4.83)
POP	__-0.0004**__ (0.0002)	-0.0004 (0.0003)	__-0.003*__ (0.002)	__0.03*__ (0.02)
POP_5YR	__0.09***__ (0.06)	__0.084***__ (0.02)	0.002 (0.09)	-0.33 (0.22)
ALFALFA	__-0.01***__ (0.002)	__-0.01***__ (0.002)	-0.02 (0.008)	0.0008 (0.005)
ALFALFA_PROD	0.0004 (0.0003)		__0.02*__ (0.008)	0.004 (0.004)
CROP_ACRE		__0.0003***__ (0.00009)		
D_AV	__1.22***__ (0.17)	__1.60***__ (0.23)	__2.19*__ (1.24)	__-2.38***__ (0.64)
N	788	788	71	179
R^2	0.80	0.82	0.77	0.41

Standard errors in parentheses. Asterisks indicate statistical significance at the 10% (*), 5% (**), and 1% (***) level.

itself also has some interesting implications. The sign for POP is negative and significant in Colorado and New Mexico, giving credence to the ideas of bigger, more experienced cities being able to negotiate a better price. Another related interpretation of this result from previous literature is that the time it takes for a party to consider an offer made to them, and then respond to that offer is itself a source of bargaining power (Binmore, Rubinstein, & Wolinsky, 1986). Larger cities with more experience and money will have attorneys and hydrologists available more readily to assess any incoming offer and will know better what is a reasonable proposal or not, and thus can respond quicker. Although the sign for POP in Nevada is positive and significant, less attention should be paid to this because there is only one metropolitan area included in the Nevada model, namely, Reno. Thus, the only variation in this variable is across years.

Marginal effects for significant predictor variables are shown in Table 13. Cells where the parameter estimate was insignificant are greyed out. Since the Ordinary Least Squares (OLS) method is used in all models, and there are no squared terms in the model, the parameter estimates themselves are the marginal effects. Table 13 shows these in terms of percentages. Because the dependent variable (LN_PRICE) is in logarithmic form, and all the independent variables shown in Table 13 are in linear form, the marginal effects stated are interpreted as the percentage change in the price that results from a one-unit increase in the independent variable being considered. First, the SPI_SNOW_V5 and SPI_URBAN_V5 variables have very large marginal effects, but since it is not possible to maintain ceteris paribus of one with respect to the other, one should be cautious when interpreting these marginal effects. It is likely the case that these effects offset each other to some extent. Among the other variables shown, POP_5YR in Colorado seems to have the largest magnitude. For every 1% increase in population growth over the last 5 years in the urban buyer's metropolitan area, the transaction price increase by 9% and 8.4% in Colorado models 1 and 2 respectively. Marginal effects for POP, ALFALFA_PROD, and CROP_ACRE are modest.

Table 13: Marginal Effects for Statistically Significant Variables

	Dependent Variable: LN_PRICE			
Independent Variable	Colorado		New Mexico	Nevada
	(1)	(2)		
SPI_SNOW_V5	**70%**	**59%**	**215%**	**-165%**
SPI_URBAN_V5	**-76%**	**-99%**	■	▨
POP	**-0.04%**	▨	**-0.3%**	**3%**
POP_5YR	**9.0%**	**8.4%**	▨	▨
ALFALFA_PROD	▨	■	**2%**	▨
CROP_ACRE	■	**0.03%**	■	■

Alternative Specifications

The models shown in Tables 12 and 13 are the main models that were settled upon after experimenting with several different specifications. These models were chosen by a two-step process: 1. Select a shortlist of models that include theoretically feasible and intuitive variables. 2. Choose between these models based on fit and presence of significance. This shortlist of models from step 1 provide a good source of results for checking the robustness of main model results. These alternative specifications can be found in Appendix F. Examining these alternative models, POP_5YR is very robust to model specification in Colorado and New Mexico. In Nevada, as alluded to before, the unexpected negative sign is not robust at all. In the main model, ALFALFA_PROD is only significant in New Mexico, and is robust to alternative specifications. The estimate for Colorado is not significant in the main model, but jumps in and out of significance in alternative models. SPI_SNOW_V5 is also largely consistent for Colorado and New Mexico, but all alternative specifications make the parameter estimate in Nevada insignificant (and the opposite sign).

Another avenue that was explored was to look at an alternative for alfalfa prices. In the main models, ALFALFA was negative in Colorado and New Mexico, and significant in Colorado. Like the outside options for buyers this is an unexpected result. In the West, almost all alfalfa produced is sold to the dairy industry for cattle feed. Therefore, it may be that as the demand for dairy products increases, so does the demand for alfalfa as an input. Depending on supply and demand forces, this may increase the MVP of alfalfa as an input, allowing farmers to charge more for alfalfa. The price of dairy in the three states may be a simple alternative to alfalfa for analyzing the outside option of the seller. Models identical to the main ones were run, but alfalfa prices were replaced by milk prices. In all three states, the sign on milk prices was the same as for alfalfa prices. These results can be seen in Appendix G. In New Mexico, significance increased a moderate amount, but in Colorado and Nevada significance dropped a large amount. Some minor effects on the significance of other variables was also observed.

Chapter 6: Implications and Future Work

Summary of Findings

In this thesis, I have built upon previous literature in recognizing that markets for water rights are often thin and are characterized by market imperfections. I have used this information to justify approaching these markets from a non-cooperative game theory perspective. Microeconomic theory predicts that both time preference and the interaction between risk and risk preferences will have impacts on observed outcomes in markets. Specifically, I have utilized and adapted the Rubinstein Bargaining Model (RBM) to model negotiations over the price of a water transaction as a function of time preference and outside options, while also incorporating risk into the model. I have utilized empirical data from three states, including some newly available data, in order to test the predictions derived from the RBM. I found moderate evidence supporting the hypothesis that urban buyers with greater time preference (more impatient) will tend to pay more for water rights. Based on the sign and significance of the measure of risk (*SPI_SNOW_V5*) associated with water sources in Colorado and New Mexico, I find some evidence supporting the conventional prediction that relative risk-aversion is a disadvantage in bargaining. Finally, no evidence was found to the hypothesis that urban buyers with a greater number of outside options should pay less due to increased bargaining power.

Theoretical Implications and Future Work

In my theoretical model, I used the results from the Nash Bargaining Model as implemented by Emerick (2007) as well as anecdotal experience to argue that a single optimal transaction quantity exists. This allowed framing the non-cooperative model as a negotiation on price only. This determination is somewhat analogous to assuming that quantity is an exogenous variable in determining price. This assumption was shown to have statistical backing through the Hausman-Wu Tests. Additionally, I attempted to incorporate an element of risk into the RBM by arguing that time preference was partly a function of the variability associated with the source of water. Making an alteration to the RBM itself to explicitly include risk as a separate parameter was not explored here. This could be an interesting avenue to pursue in future work to obtain some more specific and elegant predictions that could be tested. Another option that was not pursued here is to use a multilateral bargaining model. Rather than lump together all urban buyers and think of the Irrigation Districts as single entities, a multilateral model could allow for a more intricate analysis of how relative time and risk preferences would interact among these groups.

Empirical Implications and Future Work

Empirical models were run with data from three states, Colorado, New Mexico, and Nevada. As discussed in the previous chapter, the lack of variation across geographic space in certain variables in Nevada implies that these results are less compelling. Coefficient of variation analysis was done to check this, but results were mixed. A more detailed analysis of this issue could be done by looking at what portion of the variation in certain variables is due to year, and how much is due to zones, in order to see to what extent the data quality for Nevada is reduced due to the lack of zones. For the Colorado and New Mexico models, significance was observed in many of the variables. The level of significance in predictor variables varied a fair amount between Colorado and New Mexico, adding to the notion that characteristics of water markets are highly location and context specific. Results were fairly robust to slight alterations in the model. In fact, one or two variables that were not significant in the main model were significant in multiple alternative specifications.

The issue of obtaining quality data on water transactions has come up repeatedly in this thesis, and seems unlikely to be resolved any time soon. There a couple of pieces of data that would prove helpful in investigating various dimensions of water rights markets. First, the seniority of a water right is clearly a significant factor in deciding its value, so having access to this data would increase explanatory power of any model and make any significant effects of predictor variables more concrete. However, the effect of seniority will likely not be as large as one might expect, because the set of observed transactions will have large self-selection for seniority in the first place. Urban buyers seek out senior water rights due to their enhanced reliability during shortage conditions. Second, in the empirical analysis, I focused mainly on the characteristics of urban buyers through the Municipal Provider comparative statics, and placed less emphasis on the Irrigation District. One (but not the only) reason for this is that time preference of an agricultural producer was difficult to pin down without knowing more specific details about individual farm operations and operators. Perhaps with demographic information on individual sellers, a good proxy for Irrigation District time preference could be constructed.

A main part of the empirical analysis was concerned with finding suitable proxies to test predictions, given significant data constraints. As seen in chapter 4, there is some difference between the ideal proxies, and the empirical variables that could be obtained. A couple other ideas for other proxies were entertained, and could form part of further analysis in the future.

For cities and some other major urban buyer, it may be possible to obtain information regarding the amount of un-utilized water supply capacity owned by that entity, which would provide extra information regarding time preference (although due to available variables, this would only be possible with the Water Strategist -- of my two data sources). More specifically, the large majority of transactions that take place in these states are for surface water rights. However, municipalities that rely mainly on surface water rights will often still try to supplement these rights with groundwater stocks, which can act as a buffer in the case that surface supply is limited in any given year. An urban provider that has a significant stock of alternative water supply would have a different time preference to one that did not have this buffer, but was otherwise identical.

Looking at population, which, although a control variable in my models, provided room for some interesting hypotheses regarding bargaining experience. Instead of using population itself as a crude proxy for previous bargaining experience, it may be possible to determine, for each major buyer, the cumulative number of transactions that they have been involved in over a defined period. Another related idea would be to see if having dedicated staff (i.e. attorneys, hydrologists) on staff has an impact on prices paid for water rights by MPs.

I consider the proxy for outside options of the Municipal Provider to be the weakest of the three main proxies. One method to improve the proxy for outside options would be to obtain a relative measure of how much agricultural production (possibly for lower-value crops only) is left in the region, compared to urban water demand for that area. If there is relatively little production, then it would indicate that urban providers have few alternatives to turn to, with the exception of non-traditional water sources such as recycled water and desalination, the feasibility of which could also be investigated in future work.

Appendix A: Derivation of Time Preference Comparative Statics

The equilibrium ordinal price in the Rubinstein Bargaining Model is:

$$P^* = \frac{\delta_{ID}(1-\delta_{MP})}{(1-\delta_{MP}\delta_{ID})}$$

Taking the derivative with respect to δ_U using the quotient rule gives:

$$\frac{\partial P^*}{\partial \delta_{MP}} = \frac{(1-\delta_{MP}\delta_{ID})(-\delta_{ID}) - (\delta_{ID}-\delta_{ID}\delta_{MP})(-\delta_{ID})}{(1-\delta_{MP}\delta_{ID})^2}$$

Expanding and simplifying the numerator gives:

$$\frac{\partial P^*}{\partial \delta_{MP}} = \frac{{\delta_{ID}}^2 - \delta_{ID}}{(1-\delta_{MP}\delta_{ID})^2} \leq 0 \quad (Since\ \delta_{ID} \in [0,1])$$

Assuming the irrigation district has a discount factor $\delta_{ID} \neq 1$ changes the weak inequality into a strong one, giving us the inequality on page 28.

Employing the same tactic to the comparative static for the irrigation district:

$$\frac{\partial P^*}{\partial \delta_{ID}} = \frac{(1-\delta_{MP}\delta_{ID})(1-\delta_{MP}) - (\delta_{ID}-\delta_{ID}\delta_{MP})(-\delta_{MP})}{(1-\delta_{MP}\delta_{ID})^2}$$

Expanding and simplifying as before:

$$\frac{\partial P^*}{\partial \delta_{ID}} = \frac{1-\delta_{MP}}{(1-\delta_{MP}\delta_{ID})^2} \geq 0 \quad (Since\ \delta_{MP} \in [0,1])$$

Which again becomes a strong inequality when the MP's discount factor is strictly less than 1, giving us the inequality on page 28.

Appendix B: Municipal Provider's Outside Options Comparative Static

Recycling the logic used in the solution to the RBM, V_U can be expressed as a function of V_{ID}:

$$V_{MP} = 1 - \delta_{ID} V_{ID}$$

Rearranging the equality such that V_{ID} is on its own:

$$V_{ID} = \frac{V_{MP} - 1}{-\delta_{ID}}$$

The equilibrium price equation can be written as:

$$P^* = \delta_{ID} V_{ID}$$

Substituting the out V_{ID} gives:

$$P^* = \delta_{ID} \left(\frac{V_{MP} - 1}{-\delta_{ID}} \right)$$

Rearranging gives:

$$P^* = -V_{MP} + 1$$

Thus, the relevant comparative static is trivially calculated:

$$\frac{\partial P^*}{\partial V_{MP}} < 0$$

Appendix C: The ALFALFA_PROD Variable

The ALFALFA_PROD variable was calculated on an urban Metropolitan Statistical Area (MSA) level. A quick summary of the MSA's used can be found in Table 5. The general idea is for each MSA, to determine the counties in the given state that possess the physical and legal capacity to sell and convey water to buyers in that MSA. I will now give an overview of how this was done in each state.

Colorado

Colorado's Front Range has quite a complex system of conveyance facilities, as well as the largest number of distinct MSAs in this analysis (5). Figures 13 and 14 show county and river-based maps of Colorado. By combining the locations and paths of all rivers in Colorado, along with information on conveyance infrastructure that can transport water between rivers and basins (Coleman, 2014), a list of all counties where irrigation districts in that county can physically transfer water to each MSA can be constructed. From there, for each MSA the total production of alfalfa by year for each county on the constructed list was summed, to give a value for the number of tons of alfalfa that were produced in the counties that can supply the MSA for each year in the data.[14] Table 13 gives the counties that were included for each MSA.

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[14] In Colorado, it is the case that all counties on the West Slope that the Colorado River runs near can supply water to any of the MSAs on the Front Range, either through the South Platte River for the Northern Front Range, or through the Arkansas River for the Southern Front Range. When calculating ALFALFA_PROD, these counties are common to all, and so were not included in the totals. This does not affect the absolute difference between MSAs, but one should be cautious about interpreting marginal effects from this variable.

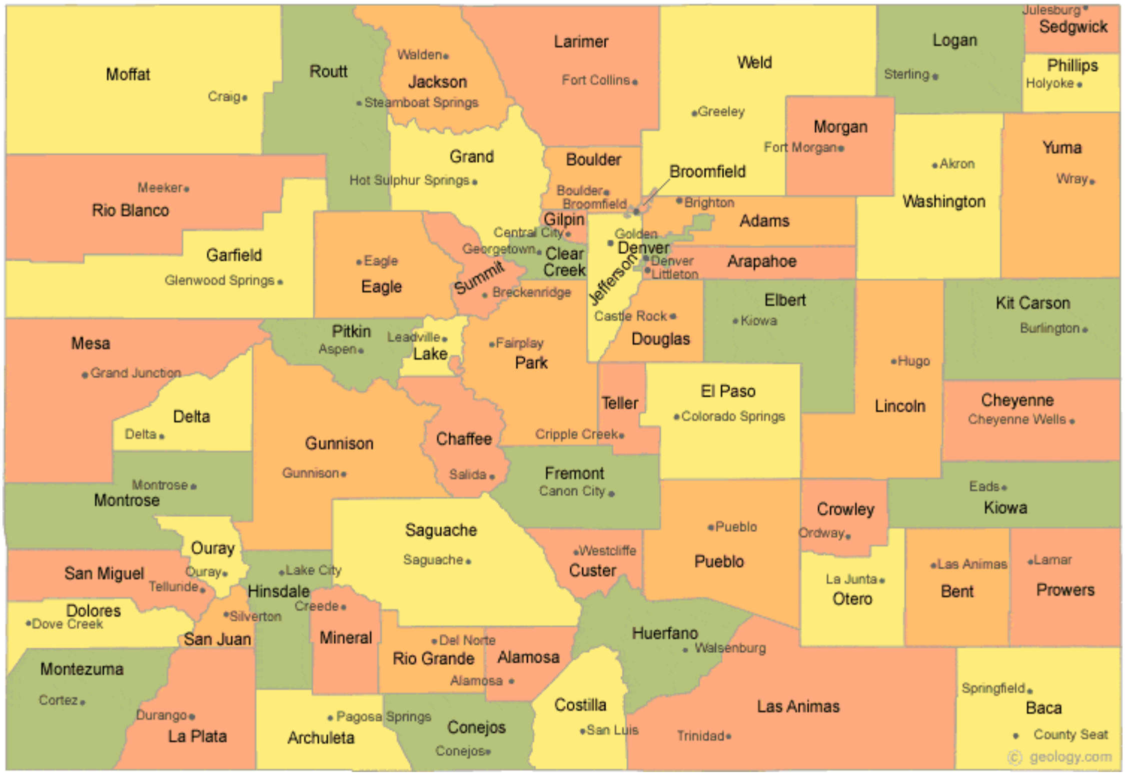

Figure 13: Colorado County Map

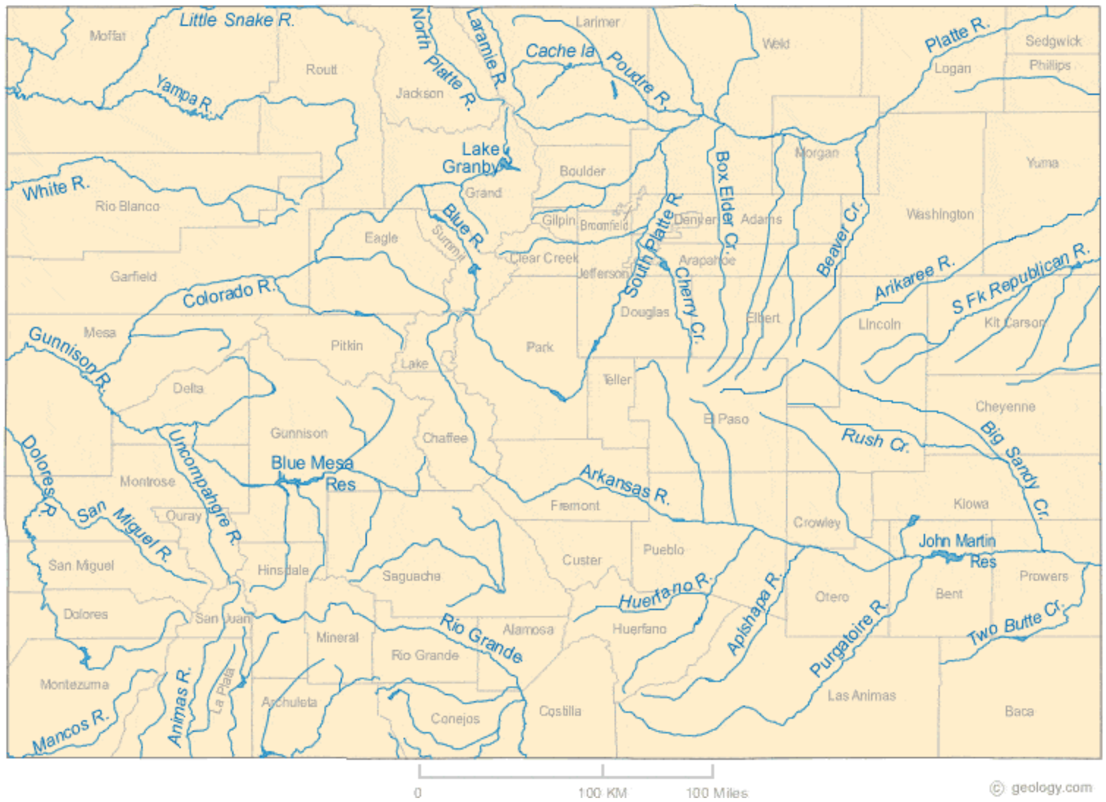

Figure 14: Colorado River Map

Table 14: Colorado Counties used in ALFALFA_PROD

Boulder, Denver, North Front Range	**Colorado Springs, Pueblo**
West-Slope CO River Counties	West-Slope CO River Counties
Adams	Baca
Arapahoe	Bent
Boulder	Cheyenne
Broomfield	Crowley
Douglas	El Paso
Jefferson	Kiowa
Larimer	Las Animas
Logan	Lincoln
Morgan	Otero
Phillips	Prowers
Sedgwick	Pueblo
Washington	
Weld	

New Mexico

New Mexico has two main rivers running north-south, the Rio Grande River and the Pecos River. This thesis focuses on the main MSAs in New Mexico, Albuquerque and Santa Fe, which both lie in the Rio Grande Basin. Therefore, I will not be concerned with the Pecos River. Figures 15 and 16 show county and river-based maps of New Mexico. The counties that can supply these MSAs are ones that the Rio Grande flows directly through. However, buyers from these areas cannot usually buy rights downstream from Elephant Butte Reservoir. In addition, Santa Fe buyers are typically prohibited from purchasing rights in Socorro and Sierra Counties. Table 14 shows the counties that were summed for Albuquerque and Santa Fe MSAs.

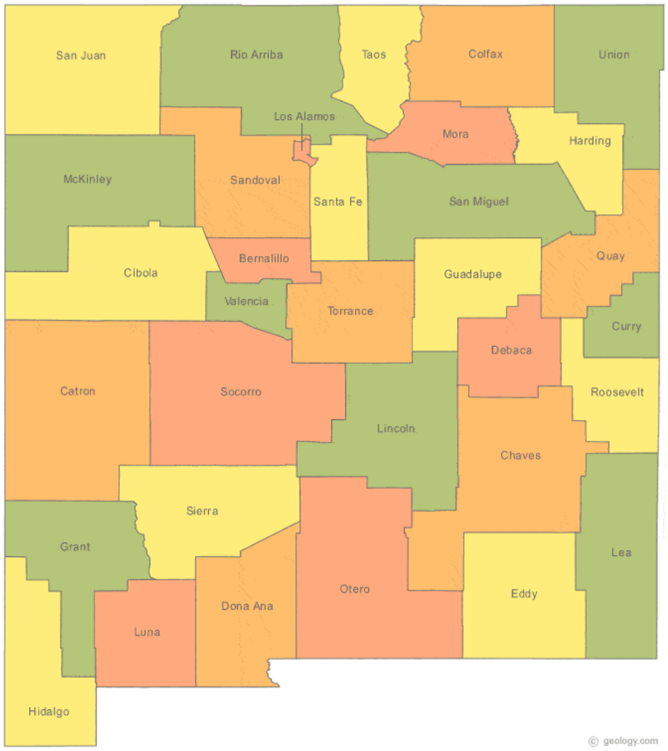

Figure 15: New Mexico County Map

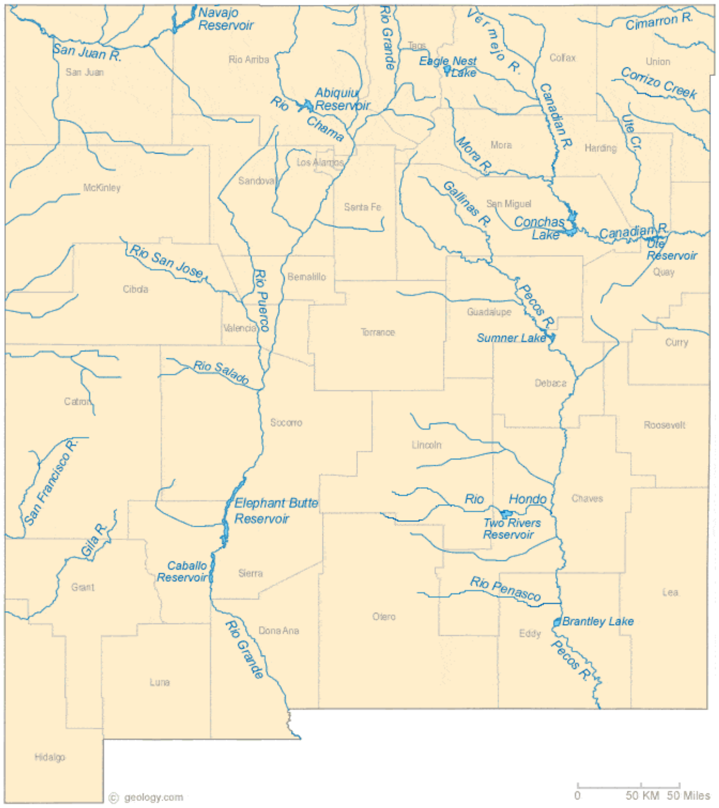

Figure 16: New Mexico River Map

Table 15: New Mexico Counties used in ALFALFA_PROD

Albuquerque	**Santa Fe**
Bernalillo	Los Alamos
Rio Arriba	Rio Arriba
Sandoval	Sandoval
Socorro	Santa Fe
Taos	Taos
Torrance	
Valencia	

Nevada

Since Reno-Sparks is the only MSA I am considering, the process of calculating ALFALFA_PROD is simple. Figures 17 and 18 show county and river-based maps of Nevada, and Table 15 shows the counties used in the calculation of ALFAFLA_PROD.

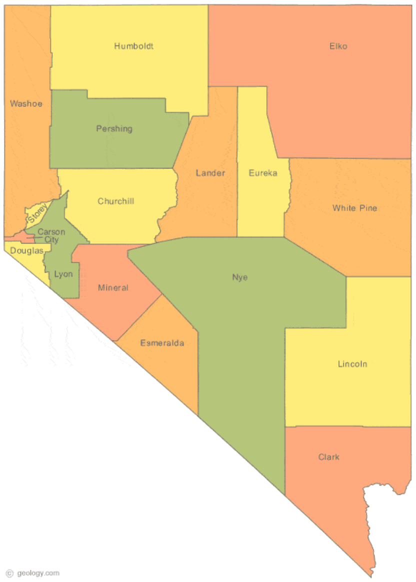

Figure 17: Nevada County Map

Figure 18: Nevada River Map

Table 16: Nevada Counties used in ALFALFA_PROD

Reno, Nevada
Carson City
Douglas
Lyon
Storey
Washoe

Appendix D: Chow Test Results and Separate Models

Table 17: Results of Chow Test

State	Test	Break Point	p-value	Reject H_0?
Colorado	Chow	2010-2011	0.0001	YES
New Mexico	Chow	2010-2011	0.0035	YES
Nevada	Chow	2010-2011	0.0069	YES

Separate Models

Collinearity was found to be an issue in the AcreValue models for New Mexico and Nevada. It seems that compared to when running combined models, there is a lack of variation in these states for *AcreValue* as the number of urban MSAs is lower. For these two models, less crucial and/or variables contributing to collinearity were removed to the point that models could be run without high/perfect collinearity.

Table 18: Estimated Parameters from Separate Models

	Dependent Variable: LN_PRICE					
Independent Variable	Colorado		New Mexico		Nevada	
	TWS	*AcreValue*	*TWS*	***<u>AcreValue</u>***	*TWS*	***<u>AcreValue</u>***
Intercept	-37.79*** (14.47)	1.78 (19.20)	-1.62 (38.60)	3.19 (1.96)	-3,692 (2.,443)	6.78*** (1.61)
LN_QUANTITY	-0.11*** (0.02)	-0.19*** (0.04)	-0.07 (0.07)	-0.14 (0.12)	0.03 (0.08)	-0.16*** (0.04)
D_LEASE	-3.78*** (0.40)	-3.29*** (0.26)	-4.26*** (0.30)	-3.19*** (0.69)		
SPI_SNOW_V5	0.52 (0.39)	-0.23 (0.50)	1.70 (0.99)	6.67*** (2.01)	-848.32 (603.80)	-0.90 (1.10)
SPI_URBAN_V5	-0.45 (0.49)	0.70 (0.45)			446.38 (317.49)	1.51 (1.78)
LN_REAL_GDP_CAP	4.56*** (1.43)	0.78 (1.93)	0.58 (3.58)		526.27 (356.22)	
POP	-0.001** (0.0005)	-0.0001 (0.0005)	-0.0006 (0.001)	0.03*** (0.009)	-1.40 (1.00)	
POP_5YR	0.09*** (0.03)	-0.02 (0.07)	0.04 (0.08)	3.34*** (1.13)	-89.84) (63.19)	0.27 (0.23)
ALFALFA	-0.01** (0.004)	-0.0006 (0.003)	0.02* (0.008)		0.85 (0.60)	
ALFALFA_PROD	0.001** (0.0004)	0.0003 (0.0008)	0.003 (0.005)	-0.17*** (0.05)	-2.49 (1.76)	0.00001 (0.002)
N	476	312	22	49	37	142
R^2	0.87	0.75	0.95	0.77	0.54	0.16

Appendix E: Hausman-Wu Tests for Endogeneity

The instrumental variable used in the test is shown below the state name. Residuals are insignificant in all three 2nd stage models. For p-values, see Table 11.

Table 19: 1st Stage Results from Hausman-Wu Test

	Dependent Variable: LN_Quantity		
Independent Variable Instrumental Variable	Colorado *SPI_L0_SNOW*	New Mexico *SPI_URBAN_V5*	Nevada *SPI_L0_SNOW*
Intercept	-45.81*** (12.42)	61.52 (0.47)	174.59 (114.28)
D_LEASE	2.66*** (0.21)	0.90 (0.08)	
SPI_SNOW_V5	-0.81* (0.44)	8.74*** (2.34)	2.80 (1.92)
SPI_URBAN_V5	1.29*** (0.47)	4.34** (1.91)	-0.82 (1.92)
LN_REAL_GDP_CAP	5.02*** (1.22)	-5.98 (7.85)	-14.50 (11.12)
POP	-0.001*** (0.0004)	-0.007*** (0.002)	-0.04 (0.20)
POP_5YR	-0.22*** (0.03)	0.03 (0.19)	0.62 (0.24)
ALFALFA	0.007** (0.003)	0.005 (0.02)	-0.005 (0.01)
ALFALFA_PROD	-0.003*** (0.0006)	0.02* (0.01)	-0.006 (0.009)
D_AV	-2.20*** (0.32)	0.63 (1.99)	1.49 (1.73)
SPI_SNOW	-0.30*** (0.11)		-0.36* (0.22)
N	788	71	179
R^2	0.42	0.41	0.08

Table 20: 2nd Stage Results from Hausman-Wu Test

	Dependent Variable: LN_PRICE		
Independent Variable Instrumental Variable	Colorado *SPI_L0_SNOW*	New Mexico *SPI_V5_URBAN*	Nevada *SPI_L0_SNOW*
Intercept	-10.81 (10.55)	-64.84 (58.13)	-100.35 (70.30)
LN_QUANTITY	-0.15 (0.19)	-0.14 (0.31)	-0.17 (0.26)
D_LEASE	-3.58*** (0.52)	-3.78*** (0.54)	
SPI_SNOW_V5	0.72** (0.31)	1.75 (2.00)	-1.56 (1.10)
SPI_URBAN_V5	-0.78** (0.32)		1.10 (0.91)
LN_REAL_GDP_CAP	2.01* (1.12)	7.07 (5.40)	9.41 (6.34)
POP	-0.0004 (0.0003)	-0.002 (0.002)	0.02 (0.02)
POP_5YR	0.09** (0.04)	0.02 (0.13)	-0.31 (0.27)
ALFALFA	-0.01*** (0.002)	-0.02* (0.01)	0.001 (0.005)
ALFALFA_PROD	0.0004 (0.0007)	0.01 (0.01)	0.003 (0.005)
D_AV	1.27*** (0.44)	2.18 (1.38)	-2.38 (0.65)
1st Stage Residual	-0.02 (0.19)	-0.08 (0.32)	0.03 (0.26)
N	788	71	179
R^2	0.81	0.77	0.41

Appendix F: Coefficient of Variation Analysis

Table 21: Coefficients of Variation by State

Variable	Colorado	New Mexico	Nevada
LN_PRICE	22.42	38.77	13.63
LN_REAL_GDP_CAP	2.20	0.61	0.81
POP	88.70	31.85	4.17
POP_5YEAR	30.27	72.06	49.77
ALFALFA_PROD	21.01	29.31	28.32

Appendix G: Alternative Main Model Specifications

The four models shown in Table 21 are a subset of the variations on the main model that were run. The numbers 1-4 correspond to:

1. Add SPI_L12_SNOW and SPI_L12_URBAN to the model
2. Remove ALFALFA_PROD from the model
3. Remove ALFALFA from the model
4. Add SPI_L12_SNOW/URBAN to the model, and use 10-year version of SPI variance instead of 5-year version

Table 22: Estimated Parameters from Alternative Models

	Dependent Variable: LN_PRICE											
Independent Variable	Colorado				New Mexico				Nevada			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
Intercept	-13.15** (6.48)	-12.77** (6.43)	-10.89* (6.58)	-10.29 (6.42)	-142.0*** (52.09)	-22.65 (38.54)	-44.09 (34.98)	-88.95 (68.31)	164.3 (120.24)	-82.38* (43.89)	-106** (49.56)	15.34 (91.93)
LN_QUANTITY	-0.17*** (0.02)	-0.18*** (0.02)	-0.18*** (0.02)	-0.16*** (0.02)	-0.23** (0.11)	-0.20* (0.11)	-0.23* (0.12)	-0.16 (0.11)	-0.14*** (0.03)	-0.14*** (0.03)	-0.14*** (0.03)	-0.14*** (0.03)
D_LEASE	-3.50*** (0.12)	-3.55*** (0.12)	-3.49*** (0.12)	-3.48*** (0.12)	-3.42*** (0.53)	-3.75*** (0.47)	-3.81*** (0.45)	-3.50*** (0.53)				
SPI_L12_SNOW	-0.05 (0.11)			0.08 (0.09)	3.84** (1.45)			-0.77 (0.58)	0.50 (0.45)			-0.05 (0.66)
SPI_SNOW_V5	0.74*** (0.26)	0.78*** (0.22)	0.19 (0.21)		17.06*** (5.15)	1.79 (1.63)	3.14** (1.43)		3.19 (2.29)	-1.27* (0.75)	-1.65* (0.84)	
SPI_SNOW_V10				1.35*** (0.46)				-3.90 (2.41)				0.70 (2.59)
SPI_L12_URBAN	-0.10 (0.09)			-0.11 (0.09)	-5.26*** (1.94)			0.56 (0.66)	0.77* (0.40)			0.67 (0.74)
SPI_URBAN_V5	-0.89*** (0.26)	-0.85*** (0.23)	0.21 (0.16)		4.12*** (1.49)	0.10 (1.36)	0.74 (1.05)		-1.39 (1.40)	1.01 (0.86)	1.09 (0.83)	
SPI_URBAN_V10				-1.80*** (0.42)				-4.63*** (1.57)				-0.70 (3.71)
LN_REAL_GDP_CAP	2.27*** (0.64)	2.25*** (0.63)	1.84*** (0.65)	2.05*** (0.63)	14.54*** (5.10)	3.03 (3.64)	4.78 (3.22)	9.77 (6.36)	-14.53 (11.02)	7.72* (4.34)	9.93** (4.82)	-0.84 (8.89)
POP	-0.001** (0.0001)	-0.001** (0.0002)	-0.0004* (0.0002)	-0.001** (0.0002)	-0.002* (0.001)	-0.0003 (0.0006)	-0.002 (0.001)	-0.002 (0.001)	-0.008 (0.02)	0.02 (0.01)	0.03* (0.01)	0.01 (0.02)
POP_5YR	0.08*** (0.02)	0.09*** (0.02)	0.08*** (0.01)	0.08*** (0.02)	0.08 (0.08)	0.09 (0.09)	0.01 (0.08)	0.23** (0.11)	0.43 (0.39)	-0.25 (0.21)	-0.34 (0.22)	-0.07 (0.23)
ALFALFA	-0.01*** (0.002)	-0.01*** (0.002)		-0.01*** (0.002)	-0.08*** (0.03)	-0.009 (0.01)		-0.02 (0.01)	0.01* (0.007)	0.004 (0.004)		0.01 (0.01)
ALFALFA_PROD	0.0006* (0.0003)		0.0008*** (0.0003)	0.0003 (0.0003)	0.01** (0.006)		0.01 (0.01)	0.008 (0.008)	0.002 (0.005)		0.004 (0.003)	0.001 (0.001)
D_AV	1.51*** (0.20)	1.19*** (0.17)	0.51*** (0.11)	1.44*** (0.16)	7.68*** (2.64)	1.12 (0.99)	0.65 (0.60)	3.75*** (1.28)	-1.86** (0.80)	-2.71*** (0.56)	-2.32*** (0.52)	-2.66* (1.55)
N	778	778	778	778	71	71	71	71	179	179	179	179
R^2	0.81	0.81	0.80	0.81	0.78	0.76	0.76	0.80	0.43	0.41	0.41	0.42

Appendix H: Models with Milk Prices

The MILK variable that replaces ALFALFA in these models is calculated in much the same way, and is also adjusted to 2016 U.S. Dollars. Significance of MILK compared to ALFALFA is better in New Mexico, but worse for Colorado and Nevada.

Table 23: Estimated Parameters from MILK Models

	Dependent Variable: LN_PRICE		
Independent Variable	Colorado	New Mexico	Nevada
Intercept	-10.94 (10.08)	-69.45* (35.63)	-106.36** (49.75)
LN_QUANTITY	-0.18*** (0.02)	-0.16 (0.10)	-0.14*** (0.03)
D_LEASE	-3.49*** (0.20)	-3.28*** (0.53)	
SPI_SNOW_V5	0.24 (0.20)	1.82* (1.06)	-1.65* (0.86)
SPI_URBAN_V5	0.17 (0.17)		1.09 (0.95)
LN_REAL_GDP_CAP	1.88* (0.99)	7.60** (3.32)	9.93** (4.85)
POP	-0.0004 (0.0003)	-0.002 (0.001)	0.03* (0.02)
POP_5YR	0.08*** (0.02)	-0.06 (0.08)	-0.34 (0.22)
MILK	-0.02 (0.01)	-0.26** (0.11)	0.0003 (0.05)
ALFALFA_PROD	0.0007** (0.0003)	0.01** (0.007)	0.004 (0.004)
D_AV	0.53*** (0.12)	1.28* (0.65)	-2.32*** (0.71)
N	788	71	179
R^2	0.80	0.79	0.41

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