DISSERTATION

MODELING THE IMPACT OF TRANSACTION COSTS, CONSERVATION AND ALTERNATIVE SUPPLY SOURCES ON WATER MARKET ACTIVITY IN THE WESTERN U.S.

Submitted by

Allison Bauman

Department of Agricultural and Resource Economics

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Doctoral Committee:

Advisor: Christopher Goemans
Co-Advisor: Dawn Thilmany

James Pritchett
Mazdak Arabi
Travis Warziniack

ABSTRACT

MODELING THE IMPACT OF TRANSACTION COSTS AND ALTERNATIVE SUPPLY SOURCES IN WATER MARKETS IN THE WESTERN U.S.

Water is an essential ingredient to growing communities, healthy ecosystems and vibrant industries. Due to increases in population, a gap between water demand for municipal and industrial (M&I) use and available water supplies is forecasted for many areas throughout the western U.S. Through the 1970's, water supply management in the West consisted of increasing water supply through building infrastructure such as dams, reservoirs and canals, but since that time, due to the high cost of new supply development, the focus has shifted to policies aimed at more effective management and reallocation of existing supplies (Chong and Sunding, 2006).

Moving forward, increased demand for water will likely be met by a combination of three means: voluntary water transfers (typically from agriculture to municipal users), water conservation, and developing new supplies/expanding existing supplies. Essentially viewing water allocation as a portfolio problem, a systematic look at performance measures (economic returns, equity, efficiency) and constraints (physical, political, economic) will contribute to better decision-making and analysis of likely outcomes and welfare changes. Accordingly, this dissertation explores impacts to M&I users, agricultural producers, and rural communities from the different means by which future demand will be met. While economists have long championed the use of water markets as a means of reallocating water from low-to-high valued uses, relatively little is known regarding how transaction costs impact the distributional

outcomes of water markets and how the portfolio of polices utilized by utilities to meet future demands, influenced by transaction costs, impacts water market activity and outcomes.

The first objective of this dissertation is to explore how transaction costs impact the functioning of water markets (economic returns, and variance across agents since equity and distributional implications may be of interest). Specifically, I consider how the presence of physical and institutional transaction costs impact producer profits, total revenues, and municipal costs for a river basin in Colorado in the presence of population growth. Contrary to previous modeling approaches, I model multiple, integrated, regional water markets consisting of agents who are heterogeneous, both in terms of objectives and situation.

The multi-objective framework adopted here is similar in concept to Kuhn & Britz (2012) and Britz, Ferris, and Kuhn (2013), but differs by including varying objective functions based on user type as well as including two types of transaction costs (infrastructure and legal), leading to different welfare outcomes due to a more accurate characterization of agent and market behavior. Although transaction costs have been included in previous water market models as a constant marginal cost (e.g., Howitt et al., 2012; Zhu et al., 2015), the novel way in which I include transaction costs is by allowing them to spatially vary, separately estimating the impacts of spatially and non-spatially uniform transaction costs. Specifically, for regional "pools" of water (e.g., ditch company) where agents face institutional transaction costs (assumed to be constant across regions) when trading within a pool, but face both institutional and physical transaction costs (assumed to vary based on the location of the buyer and seller) when trading across pools.

Results from the model demonstrate the importance of including heterogeneous transaction costs into a water market model as these costs have a large impact on the welfare outcomes associated with water markets, both in terms of overall efficiency and distributional impacts. Producers that own water rights earn positive profits in the face of population growth because they are able to sell their water rights on the water market, but those gains vary greatly across users based on their location within the basin; this difference is driven by transaction costs, and largely by the physical transaction costs that vary based on location. In essence, water market outcomes are place-based, an important consideration for those interested in distributional fairness and rural-urban economic development linkages.

One key result from this modelling effort is that, despite increasing agricultural revenues, the elimination of transaction costs-something targeted to help rural communities- reduces overall profits to agricultural producers. Farmers earn lower total revenues due to a decrease in the number of acres being farmed, and this decrease in revenue has a negative impact on those in the agricultural communities that support farmers, creating a decrease in local economic activity and particularly for those sectors and agents close to the agricultural industry. For M&I water customers in water scarce regions, a reduction of transaction costs will lead to a lower price for municipal water. For M&I water customers in water rich regions, there will be no change in price from a decrease in physical transaction costs.

The second objective of this paper is to answer the following research questions: one, what is the impact of introducing M&I conservation and new supply into a water market on the costs to meet future demand for water? And two, what impact does introducing M&I conservation and new supply into a water market have on the welfare of agricultural producers and the economic activity of rural communities? Again, this provides a more complete evaluation of how managing the water market portfolio may require consideration of factors that may vary by location and agent, a complexity important to address for a good and markets with so a high degree of heterogeneity for supply and demand, like water.

While there is evidence from the literature that conservation can lead to an increase in overall regional welfare (Gillig, McCarl, and Boadu, 2001; Rosenberg, Howitt and Lund 2008), it is unclear how conservation impacts producers and how a producer's location within a basin might relate to those impacts. Conservation has been promoted, in part, to help agricultural and rural communities, but how producers will be impacted by conservation is largely unknown. Contrary to the previous literature, the focus of my study is not the least cost means by which to meet future demand for water. Instead, this study explores the welfare impacts of a water market in which M&I firms can meet future demand through a portfolio approach, including purchasing water on the market, through new supply development, and/or through conservation. I expand on Zhu, Marques, and Lund (2015) to include heterogeneity across water user type, location, and transaction costs as well as to evaluate the welfare impacts of both conservation and new supply.

Some proponents of the portfolio approach to meeting future demand for water claim producers will be better off because more water will remain in agriculture. Results from the model show that, in the aggregate, conservation and new supply may actually harm agricultural producers with a decrease (albeit small) in the present value of a future stream of total profits earned by most producers in the South Platte River Basin. While more water remains in production when conservation and new supply are utilized, this is offset by the fact that fewer water rights are sold and at a lower price. But for the individual producer, the impact of the portfolio approach on profits can be significant if that producer was likely to sell all of his or her water rights absent conservation/new supply. This type of producer will not be made better off, as a decrease in the price of a water right will mean less profits received from their sale.

In addition to modelling regional water market activity, I use an input-output model to estimate changes in regional economic activity under the different scenarios. In essence, this could be considered a simulation of portfolio outcomes linked to the estimates from the earlier modelling water markets, but focused on just the economic returns to key players in the market. Overall, conservation and new supply lead to positive regional economic impacts, but for water scarce regions with high population growth, without considering potential positive impacts of M&I conservation (e.g., installing a low-flow toilets creates jobs), conservation can have small negative economic impacts. This is contrary to popular belief that retaining more water in agriculture leads to economic gains for rural communities. The small, negative economic impact results from changing market dynamics due to decreased M&I demand, leading to a sharp decrease in price for water scarce regions with high population growth. The magnitude of economic impacts decreases as a higher proportion of proceeds from the water market are assumed to be spent locally. The positive economic impacts resulting from increased revenue from production are partially offset by the negative economic impacts from decreased revenue from the water market.

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DEDICATION

To my family. Thank you for all of your love and support.

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Chapter 1: Introduction

Water is an essential ingredient to growing communities, healthy ecosystems and vibrant industries. Due to increases in population, a gap between water demand for municipal and industrial (M&I) use and available water supplies is forecasted for many areas throughout the western U.S. For example, population in Colorado is projected to nearly double by 2050 requiring an additional one million acre/feet of water per year, yet unappropriated water in Colorado is extremely limited (SWSI, 2011). Through the 1970's, water supply management in the West consisted of increasing water supply through building infrastructure such as dams, reservoirs and canals, but since that time, due to political tension and the high cost of new supply development, the focus has shifted to policies aimed at more effective management and reallocation of existing supplies (Chong and Sunding, 2006).

Increased demand for water will likely be met by a combination of three means: voluntary water transfers (typically from agriculture to municipal users), water conservation, and developing new supplies/expanding existing supplies. Essentially viewing water allocation as a portfolio problem, a systematic look at performance measures (economic returns, equity, efficiency) and constraints (physical, political, economic) will contribute to better decision-making and analysis of likely outcomes and welfare changes. In Colorado, most expect voluntary transfers to play the largest role, current forecasts suggesting that as much as 70% of the 2050 municipal and industrial water demand will be met by voluntary transfers from agriculture (SWSI, 2011). The remaining portion of the supply gap will be met by increasing supply through building new and expanding existing infrastructure and reducing demand through conservation.

This dissertation explores impacts to M&I users, agricultural producers, and rural communities from the different means by which future demand will be met. While economists have long championed the use of water markets as a means of reallocating water from low-to-high valued uses, relatively little is known regarding how transaction costs impact the distributional outcomes of water markets and how the portfolio of polices utilized to meet future urban demands- also influenced by transaction costs- impact water market activity and welfare outcomes. There are two sets of discussions occurring throughout the West with respect to water resource management. One, should existing water supplies be reallocated to meet increased demand for water resulting from population growth? And if so, how should water be reallocated and what are the resulting impacts? And two, what are the implications of using a "portfolio approach" to water resources management planning, including both supply augmentation and demand reduction measures as a means by which to meet increased demand for water?

Chapter 2 contributes to the first discussion by exploring the effectiveness of water markets given existing institutional and physical constraints and the resulting impacts to M&I firms, producers, and rural communities. The first objective of this chapter is to explore how transaction costs impact the functioning of water markets (economic returns, and variance across agents since equity and distributional implications may be of interest). Specifically considering how the presence of physical and institutional transaction costs impact producer profits, total revenues, and municipal costs for a river basin in Colorado in the presence of population growth. Contrary to previous modeling approaches, I model multiple, integrated, regional water markets consisting agents who are heterogeneous, both in terms of objectives and situation.

Chapter 3 contributes to the second discussion by exploring the impact of measures that seek to leave more water in agriculture (i.e., conservation and new supply development) on M&I cost to acquire water, producer profits, and the well-being of rural communities. The objective of this chapter is to answer the following research questions; one, what is the impact of introducing M&I conservation and new supply into a water market on the costs to meet future urban water demands? And two, what impact does introducing M&I conservation and new supply into a water market have on the welfare of agricultural producers and the economic activity of rural communities? Again, this provides a more complete evaluation of how the impacts of water markets may vary by location and firm, a complexity important to address for markets with a high degree of heterogeneity for supply and demand, like water. The modeling framework of a water market with current institutional and physical constraints is developed in Chapter 2 and modified in Chapter 3 to also include the choice of M&I conservation and new supply development, thereby adding the flexibility necessary to model the use of a portfolio approach to meet future demand for water.

The remainder of this dissertation is organized as follows. Chapter 2 explores how transaction costs impact the functioning of water markets, examining how much water is sold from producers to M&I firms and where those trades take place, producer profits and revenues, and M&I costs under a range of transaction cost scenarios. The chapter begins with an introduction and background focusing on water markets and transaction costs. The third section of the chapter presents the modeling framework, including a conceptual framework for the model as well as a mathematical representation. The fourth section of the chapter presents results from the optimization model, focusing on the impact of transaction costs on M&I costs, producers' profits, and regional economies. The chapter ends with concluding remarks.

Chapter 3 explores the impact of conservation and new supply development on regional economies in the presence of a water market, including impacts to both agricultural and urban water users. The chapter begins with an introduction and background focusing on a portfolio approach to meet future demand for water. The third section of the chapter extends the modeling framework presented in Chapter 2 to also include the choice of conservation and new supply, including the conceptual framework of how conservation and new supply impact the water market as well as the mathematical representation. The fourth section of the chapter presents results from the optimization model discussing how the introduction of conservation and new supply impact M&I costs, producer profits and revenues, as well as regional economies. The chapter ends with concluding remarks. Funding for this work was generously provided by the USDA-National Institute of Food and Agriculture (NIFA) Grant # 2012-67003-19904.

Chapter 2: Estimating the Impact of Transaction Costs in a Water Market

Market based, voluntary transfers of water have long been promoted by economists based on the idea that, under perfectly competitive market conditions, they lead to an efficient allocation of water (Booker &Young, 1994; Chong & Sunding, 2006; Booker, et al., 2012). Substantial transaction costs associated with transferring water via existing water markets have limited the exchanges that have occurred in the past, resulting in efforts to reduce these costs with the hope of increasing the utilization of water markets (Iseman, et al., 2012; SWSI, 2011). Critics of water markets note that changing water allocations can lead to significant negative economic impacts to rural communities when water is removed from agriculture and transferred to uses outside of the original area of use (Booker, Howitt, Michelsen, & Young, 2012; Bourgeon, Easter, & Smith, 2008). Increased water market activity resulting from reduced transaction costs would potentially increase these negative impacts. The objective of this paper is to explore how transaction costs impact the functioning of water markets and the distribution of outcomes experienced by different segments of society. The latter includes examining- across a range of transaction cost scenarios- how much water is sold from agricultural producers to M&I users and where those trades take place, producer profits and revenues, and the cost born by M&I users to meet future demands.

The increased reliance on water markets to reallocate water across the West has led to greater attention being directed at how water markets function. Both empirical studies on water markets as well as optimization and simulation modeling approaches have been used to examine water markets. Empirical studies have primarily focused on characterizing historic market activity, generally finding that the price of water varies widely based on the institutional setting and the characteristics of the water right being traded. Key factors influencing price and quantity transferred include: (a) whether or not the transaction involves a change in use or location, (b) the relative reliability of the water right (i.e., seniority), and (c) the presence of physical and/or institutional transaction costs (Colby, Crandall & Bush, 1994; Pullen & Colby, 2008; Payne, Smith & Landry, 2014). The main shortcoming of using an empirical approach to analyze water markets is a lack of reliable data.

Due to this lack of reliable data, optimization and simulation modeling approaches are often utilized to examine water markets. Optimization/simulation studies have been used to quantify potential welfare gains associated with using markets to reallocate water across uses (Booker & Young, 1994; Booker, Rosegrant et al., 2000; Michelsen & Ward, 2005). One of the main shortcomings of previously utilized optimization modeling approaches is the assumption of perfectly competitive market conditions. This is done, in part, because a water market can be easily modeled using a single objective function. But, a perfectly competitive market structure assumes that transaction costs are zero and all users are homogenous; which the empirical literature on water markets has shown to not be true (Brookshire, Colby, Ewers & Granderton, 2004; Colby, 1990; Payne, Smith & Landry, 2014).

Building from previous optimization modeling approaches, I model multiple, integrated, regional water markets consisting of two sets of heterogeneous decision makers: agricultural producers (Producers) and M&I agents. Heterogeneity exists across sets (different objective functions), as well as within (variability in physical characteristics and location). Producers are assumed to maximize expected profit; whereas the goal of M&I agents is to minimize the cost of acquiring enough water rights to meet forecasted demand. Consistent with development practices throughout much of the West, M&I demand for water is based on projected growth, current consumption of water, and a reliability factor[1] (Howe & Smith, 1994).

The multi-objective framework adopted here is similar in concept to Kuhn & Britz (2012) and Britz, Ferris, and Kuhn (2013), but differs by including different objective functions based on user type as well as including transaction costs, leading to different welfare outcomes due to a more accurate characterization of agent and market behavior. Although transaction costs have been included in previous water market models as a constant marginal cost (e.g., Howitt et al., 2012; Zhu et al., 2015), the novel way in which I include transaction costs is by allowing for regional "pools" of water (e.g., ditch company) where agents face institutional transaction costs (assumed to be constant across regions) when trading within a pool, but face both institutional and physical transaction costs (assumed to vary based on the location of the buyer and seller) when trading across pools.

Transaction costs in a water market can be defined as:

- The resources used to define, establish, maintain and transfer property rights (McCann, et al., 2005);
- the costs for water transfers from identifying opportunities, negotiating transfers, monitoring third-party effects, conveyance, mitigation of third-party effects, and resolving conflicts (Rosegrant & Binswanger, 1992), or;
- the costs that occur when obtaining state approval to transfer a water right; which include attorney's fees, engineering and hydrologic studies, court costs, and fees paid to state agencies (Colby, 1990).

[1] To meet future demand for water, M&I firms buy the firm yield of a water right, rather than the consumptive use portion of average diversion amount that is used by producers. This is based on the idea that municipalities seek to minimize the risk of a shortfall in water during drought years; the amount of water that is assumed a water right will yield is not based on average diversions, but rather diversions in times of drought (i.e. firm yield).

In this paper, I split the transaction costs associated with transferring water rights into two categories: institutional and physical transaction costs, where institutional transaction costs are assumed to be homogenous across regions while physical transaction costs are not. To prevent negative impacts to other water rights holders, state governments regulate water rights transfers (for a more detailed discussion, see Gretches, 2009). These regulations result in additional costs for the buyer/seller (Colby, 1990). Herein, I refer to these as institutional transaction costs.

Alternatively, there can also be costs associated with moving water from one location to another due to the absence of infrastructure. I refer to these costs as physical transaction costs. The magnitude of both institutional and physical transaction costs vary depending on the nature of the transfer (e.g., the location of the old versus new use, the nature of the old versus the new use, etc.). Given the relatively large transaction costs associated with water transfers, there have been efforts in many Western states to reduce transaction costs in water markets (Iseman, et al., 2012), most of which have focused on institutional transaction costs. Despite these efforts, little is known about the impact that transaction costs have on water markets and those whom participate

The location of a water right in relation to existing infrastructure, the upstream/downstream location, and the previous use of a water rights have different physical and institutional transaction costs associated with transferring water. Payne, Smith and Landry (2014) found that transaction costs, both institutional and physical, account for the majority of the variation in the price of water shares in the South Platte River Basin. Colby (1990) found that the legal costs associated with transferring water in Colorado from 1980-1989 accounted for around 12% of the total price of a water right.

In an agreement between a group of municipalities in the Denver metro region in Colorado in 2009 to acquire water and build new infrastructure, infrastructure costs were about 35% of the price of water (ACWWA, ACWWPID, ECVV, United, United ACWWA Enterprise, United Chambers Enterprise, 2009). It is clear that significant transaction costs exist due to physical and institutional constraints, and at some level they impact market activity. What is not clear is how and what would happen if we reduced or eliminated transaction costs.

In contrast to previous studies, I assume (1) producers and M&I agents have different objective functions, (2) two types of transaction costs exist, and (3) heterogeneity exists in the market commodity being traded as a result of heterogeneous transaction costs. My main research question is: how does the presence of transaction costs in water markets impact welfare outcomes, in terms of overall efficiency and distributional impacts? In order to answer this question I first explore the impact of population growth given the current institutional setting (i.e., the existence of physical and institutional transaction costs).

Next, I explore the impact of reducing transaction costs on the quantity and location of water traded, producer profits, and M&I costs to meet long-run demand for water. The impact of three types of transaction costs will be considered: institutional transaction costs (assumed to be homogenous across regions), physical transaction costs (assumed to be heterogeneous across regions), and both types of transaction costs. Lastly, I evaluate how regional economies will change as a result of water trading due to long-run population growth, evaluating the impact with and without transaction costs. My research question will be answered by:

a) Developing an individual optimization framework that results in a measure of economic welfare for heterogeneous producers and M&I agents that engage in trading on a water market with heterogeneous transaction costs.

b) Parameterizing the model with data from the South Platte River Basin in Colorado and analyzing changes in welfare outcomes and important endogenous variables as two types of transaction costs, institutional and physical, are reduced.

I expect results from this paper to show that heterogeneous agents and the existence of transaction costs play a role in welfare outcomes from the water market, showing the importance of a modeling approach consisting of multiple, integrated, regional water markets with heterogeneous agents, both in terms of objectives and situation to provide more nuanced policy and market analysis. As institutional transaction cost decrease, water will be less expensive for all water users to purchase, regardless of their location. This will lead to less expensive water for the main buyers of water, municipalities. The influence on the price of water received by sellers is likely to be minimal given the perfectly inelastic nature of municipal demand. As physical transaction costs decrease, the transaction costs paid by buyers will be less expensive. Because the regional differences in physical transaction costs drive the price received by buyers in each region on the water market, the impact to producers is unknown and largely dependent on market dynamics. While the amount of water producers transfer to municipalities will not change as transaction costs change, where the water comes from and the resulting producer welfare is unknown.

The remainder of this chapter is organized as follows. The background section describes how water markets have been modeled in the previous research, results from the empirical studies of water markets, as well as how the model developed in this paper fits into and adds to the current literature. Next, the water rights allocation section describes the methodological framework for the model developed in this paper, including the producer problem, the municipal problem, and a discussion of the impact of transaction costs on market equilibrium. Next, the data and calibration presents the data used in the simulation portion of the study as well as how the model was calibrated. The results section describes the impact of population growth on producer profits and M&I costs, the impact of transaction cost on the quantity and location of water traded, producer profits, and M&I costs to meet long-run demand for water, as well as the impact of population growth and transaction costs on regional economies. The paper ends with concluding remarks.

2.1 Background: Transaction Costs in a Water Market

Due to lack of available data, voluntary water transfers are commonly modeled using holistic water resource models (often termed hydro-economic models) that capture the spatial nature of the basin while establishing a linkage between the economic and hydrologic properties (Cai, 2008). Hydro-economic models can be either simulation or optimization models, typically utilizing the node-based river management system or the economy wide general equilibrium approach (Bekchanov, Sood, & Jeuland, 2015) and have been used extensively to examine water markets (Harou, et al., 2009 survey many approaches, current examples include Rosegrant, et al., 2000; Booker, Michelsen, Ward, 2005; and Howitt, et al., 2012).

A common feature of hydro-economic models is the use of a single objective function that maximizes net benefits (e.g., Rosegrant, et al., 2000; Booker, Michelsen, Ward, 2005), which in turn, assumes perfectly competitive market structure. A single objective function allows researchers to simplify the problem at hand, but assumes that all water users make decisions to maximize total welfare in the basin; in reality, water users make decisions based on their individual welfare. Aggregating individual decisions into a single objective is relatively straightforward when all users have similar objectives (e.g., max profit, max utility, etc.). However, this approach is difficult when the nature of each individual's optimization problems vary substantially, as is the case in a water market in which there are two types of participants with differing objective functions: producers and municipalities.

The assumption of perfect competition presumes the water market is characterized by a large number of buyers and sellers, no barriers to entry or exit, profit maximizing behavior, homogeneous goods, perfect factor mobility, perfect information, non-increasing returns to scale, well defined property rights, no externalities, and zero transaction costs. Although it appears that the reality is that there are few buyers and many sellers, imperfect information, non-profit maximizing behavior, heterogeneous goods, and relatively large transaction costs persist in the water markets in many river basins (Colby, 1990; Timmins, 2002; Howe & Goemans, 2003; Iseman, et al., 2012).

In the western U.S., when a municipality provides a permit to build a new development or property, they typically require the developer of the property to purchase the right to use a specific quantity of water or cash in lieu for each new water tap before they are given the permit to build (e.g., City of Loveland, 2016). The amount of water each municipality requires to be purchased varies[2], but traditionally, municipalities require developers to secure enough water to maintain system reliability given the additional demand associated with the new tap, often called firm yield (Griffin & Mjelde, 2000).

As a result, water rights purchases to meet population growth are not based on customers' willingness to pay for water, rather they are based on the number of new water taps times average gallons per capita day (GPCD) consumption of water per household plus a reliability factor; evidence suggests the reliability is not in line with welfare (Howe & Smith, 1994). In most water market models that utilize the typical benefit maximization framework that results

[2] The amount of water each municipality requires to be purchased varies across cities or within a city across time, but is constant for a given customer class within a city at a given time.

from a single objective function, the municipality minimizes the cost of acquiring water subject to an optimal level of consumer utility[3] rather than subject to a minimum water supply level. The latter typically leads to purchasing a more reliable amount of water than the former because the former implies a tradeoff between water and other goods, the latter does not. One example of a water market model that includes a single objective function that differs is Zhu, Marques, and Lund (2015), in which the cost of acquiring water is included in a single objective function subject to meeting a minimum level of water supply.

In the majority of hydro-economic models with both producer and M&I agents, M&I agents maximize a net benefit function derived from consumer demand for water (e.g., Rosegrant, et al., 2000; Babel, Gupta, & Nayak, 2005). My approach, on the other hand, seeks to model the idea that M&I agents choose a net water requirement per household and require developers to secure the water or provide cash in lieu of purchasing it themselves (City of Loveland, 2016), rather than purchasing water based on consumers' willingness to pay for water; a similar approach was utilized in Zhu, Marques, and Lund (2015). Either the developer or the municipality then purchase the cheapest combination of water rights that secure the firm-yield requirement. By setting up the M&I problem in this manner, (a) the requirement of firm yield requires M&I firms to secure water rights that meet a city determined level of reliability, and (b) this is not the social planner's problem unless the M&I firm's pre-determined level of reliability is socially optimal.

Some hydro-economic models do utilize varying objective functions, although none in the same manner as described in this paper. In a model constructed by Babel, Gupta, and Nayak (2005) the objective function is the same across users but the user can choose to maximize one or both of the following objectives: to maximize satisfaction and to maximize the net economic

[3] Optimal level of consumer utility is based on consumer's willingness to pay for water

benefit by the demand of water users (agriculture, domestic, industry, hydropower, recreation and environment). A weighting technique is then utilized to convert the two objective functions into one. Similarly, Han, Huang, Wang, and Maqsood (2011) and Davijani, Banihabib, Anvar, & Hashemi (2016) allocate water based on differing objective functions. In both cases, objective functions are conflicting, rather than just being different and are not different for each individual in the model. While previous research has utilized differing objective functions, to my knowledge, none have modeled both multiple and differing objective functions as I do in my model.

Another common feature of hydro-economic models, resulting from the assumption of perfect competition, is the characterization of water as a homogeneous good. When a model optimizes a single objective function, water seamlessly moves across water users in the basin up to the point where the marginal value of water is equated across users. All water is treated the same, regardless of the location or priority, and there is no cost associated with transferring the water,or if there is, it is a constant marginal cost that does not vary depending on the location of the water user (e.g., Howitt et al., 2012; Zhu, Marques, and Lund, 2015). This is contrary to the physical and institutional reality of water markets; when transferring a water right, there is an associated institutional and physical cost and that cost differs across users.

Two types of transaction costs persist in water markets: institutional (non-location specific) and physical (location specific). In this paper, I assume institutional transaction costs do not vary across regions whereas physical transaction costs differ depending on the location of the buyer and seller. From the empirical research on water markets, we know that the price of water is largely influenced by the heterogeneous nature of water and that much of the heterogeneity in a water right can be considered transaction costs, both institutional and physical. Transaction costs have been one of the more discussed aspects of water markets both publically and in the literature and yet they have been rarely accounted for in water market models (Garrick & Aylward, 2012). Analysis of the impact of transaction costs on market activity will focus on the institutional and physical costs associated with transferring water in this research.

Colby, Crandall and Bush (1994) find that geographic flexibility, priority date, quantity of water purchased, and type of buyer all had a statistically significant influence on the price of a water right in water markets in the western U.S. Geographic flexibility had the largest impact on the price of water; the water rights located in the sub-basin that were more easily transferred to a new location and new use were significantly more expensive that those rights that that were not. The transaction costs, both conveyance and legal, between transferring the two types of water rights were hypothesized to play a role in the price.

Brookshire, Colby, Ewers & Granderton (2004) analyze three different water markets in the western U.S. with differing levels of heterogeneity among the water rights. They analyze the Colorado Big Thompson water market in Colorado, a market with homogenous water rights and low costs associated with transferring water rights. This market has significantly more trades and a higher price of water compared to the other water markets studied with a higher degree of heterogeneity among water rights and high cost to transfer water. Their findings demonstrate that transaction costs associated with transferring water have a significant impact on both the price and quantity of water traded.

Pullen & Colby (2008) find that the quantity of water transferred, the location where a transfer occurred, if a water right changed to a new use, and if a transaction occurred in a drought year all have a statistically significant impact on the price of water. They find that the price of a water right located in the sub-basin from which water is more easily transferred out of and appropriated to a new use (i.e. low infrastructure and legal transaction costs) is approximately 86% higher compared with the sub-basin for which water transfers outside of the sub-basin and to a new use are very difficult and expensive (i.e. high infrastructure and legal transaction costs).

Payne, Smith, and Landry (2014) analyze the water market for ditch company shares in the South Platte River Basin in Colorado. They find that the three variables with the largest influence on the price of water rights are shares from a specific ditch company with a reservoir ideally located near current infrastructure for many growing municipalities (increase price by $11,164), the previous use of the water right (decrease price by $7,479 if the previous use is agriculture compared to municipal), and if the water right is located in the upper portion of the basin (increase price by $4,434). All three variables can be thought of as transaction costs. The location of a water right in relation to existing infrastructure as well as the upstream/downstream location in the basin have different infrastructure transaction costs associated with transferring water and the previous use of the water right will influence the legal transaction costs associated with a water transfer. They find that transaction costs, both institutional and infrastructural, account for the majority of the variation in the price of water shares in the South Platte River Basin.

Transaction costs increase the cost of transferring water and thus play a role in how efficiently water is transferred between water users. When not included in a water market model, trading is likely to be overstated and actual welfare outcomes could be different than predicted by the model, leading to misinformed policy recommendations. Although transaction costs have been included in previous water market models as a constant marginal cost (e.g., Howitt et al., 2012; Zhu et al., 2015), the novel way in which I include transaction costs is by allowing for regional "pools" of water (e.g., ditch company) where agents face institutional transaction costs (assumed to be constant across regions) when trading within a pool, but face both institutional and physical transaction costs (assumed to vary based on the location of the buyer and seller) when trading across pools.

2.2 Water Rights Allocation Model

Assume there are *i* firms in a river basin consisting of both agricultural and M&I firms. Agricultural producers differ based on the crop they produce and the region in which they are located and maximize profit by using water in production, buying water, and selling water. M&I firms differ based on their demand for water and the region in which they are located and choose to buy water today to meet forecasted future demand for water with the objective of minimizing the cost of buying water. Consistent with development practices throughout the West, we assume that M&I firms are required to purchase supplies such that the firm yield of the water rights they purchase is greater than or equal to forecasted demand[4]. This is based on the idea that municipalities seek to minimize the risk of a shortfall in water during drought years; the amount of water that is assumed a water right will yield is not based on average diversions, but rather diversions in times of drought (i.e. firm yield).

Each user faces two types transaction costs associated with buying water from other users: physical transaction costs, the magnitude of which depend on their location relative to existing water rights owners, and legal transaction costs which remain the same for all water buyers in the region. I model this by creating different "pools" of water. When purchasing water from one's own regional pool, a firm faces institutional transaction costs only. When purchasing water from an outside regional pool, a firm faces both institutional and physical transaction costs. The price of water rights in each pool is endogenously determined, reflecting supply, demand and transactions costs throughout the region. (see Figure 1).

[4] All water in the model is in terms of consumptive use.

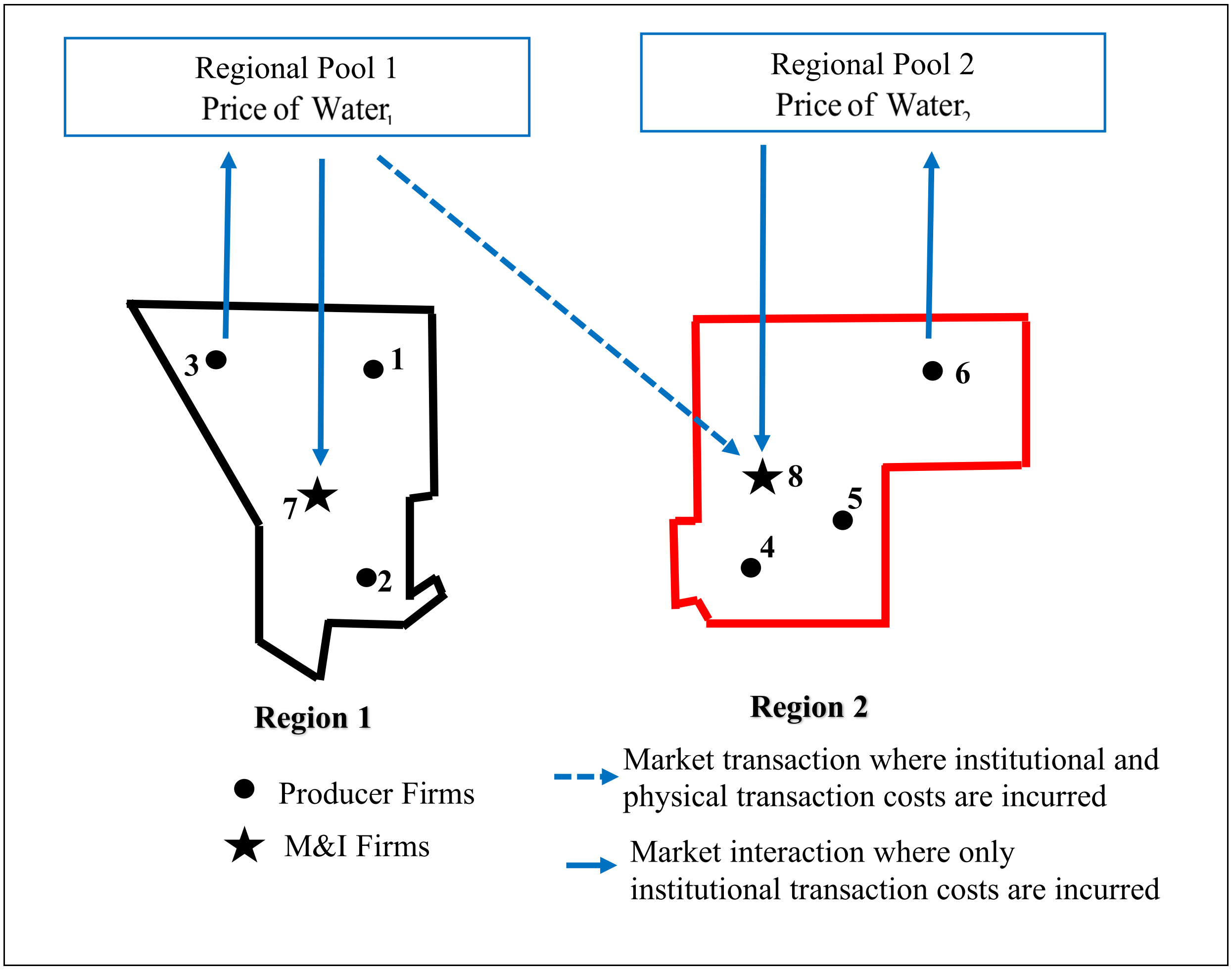


Figure 1. Conceptual framework of market interaction between buyers and sellers when transaction costs are present

The remainder of this section will begin with a detailed discussion of the producer problem, municipal problem, and market interaction and transaction costs, and conclude with an example of a water market with two regions, each consisting of one municipal and one producer firm.

2.2.1 Producer Problem

Producers maximize profit by choosing the amount of water and acres to use in production as well as the amount of water to buy or sell on the water market, which consists of multiple regional pools. The producer profit maximization problem is as follows[5]:

$$
\begin{aligned}
&\max_{w,A,s,b} \quad \pi_i = P_{y,i}F_i(w_i, A_i) - c_{w,i}A_i w_i - c_{A,i}A_i + \sum_r \left(P_{w,r}s_{i,r} - P_{w,r}b_{i,r} - tc_{i,r}(b_{i,r}) \right) \\
&s.t. \\
&\qquad w_i \geq 0 \\
&\qquad A_i \geq 0 \\
&\qquad s_{i,r} \geq 0 \\
&\qquad b_{i,r} \geq 0 \\
&\qquad w_i A_i + \sum_r s_{i,r} \leq \overline{W}_i + \sum_r b_{i,r} \\
&\qquad A_i \leq \overline{A}_i
\end{aligned}
\qquad (1)
$$

where $P_{y,i}$ is the output price per unit for producer *i*. Each of the *i* producers differ in the crop they produce and/or the region in which they are located and has a unique production function. $F_i(\cdot)$ is the production function for producer *i* describing output where w_i is water use per acre by firm *i*, A_i acres used in production by producer *i*, $c_{w,i}$ is the cost per unit of using water in production for producer *i*, and $c_{A,i}$ is the cost of production per acre for producer *i*.

$P_{w,r}$ equals the price per unit of water bought/sold from regional pool *r*, $s_{i,r}$ is the amount of water sold by producer *i* into regional pool *r*, and $b_{i,r}$ is the amount of water bought by producer *i* from regional pool *r*, and $tc_{i,r}(b_{i,r})$ is the transaction cost as a function of water

[5] Based on Colorado water law, producers can only sell the consumptive use portion of their water right, defined as a water use that permanently removes water from its source (Hobbs Jr., 2004). Therefore, only the consumptively used portion of a producer's water right is included in this model.

bought that is incurred by firm *i* from transferring water from regional pool *r*. Transaction costs, $tc_{i,r}$, consist of two types of transaction costs, institutional and physical where $tc_{i,r} = tcI_{i,r} + tcP_{i,r}$. I assume the technology set for each producer is convex, monotonic, closed, bounded, and non-empty (e.g., $F_i^{'}(\cdot) \geq 0, F_i^{''}(\cdot) \leq 0 \ \forall_i$). Each producer is endowed the consumptive use portion of their current endowment of water, $\bar{W}_i$, calculated as a percentage of average diversions and $\bar{A}_i$ is initial endowment of acres for producer *i*.

Output price, the cost and initial endowment of water and land, and transaction cost are assumed exogenous. Water use, acre use, price of water, and the quantity of water bought and sold on the market are endogenously determined. Producers choose the amount of water to use in production and the amount to buy/sell on the market that maximizes profit. The first four constraints ensure non-negative input use or water transfers. The fifth constraint constrains water use by ensuring the total amount of water used in production plus the amount sold on the water market is be less than or equal to the amount of water endowed to the producer plus the amount acquired on the water market. The last constraint ensures land use will be less than or equal to the amount of land endowed to each firm.

The resulting Lagrangian is as follows:

$$L_i = P_{y,i}F_i(w_i, A_i) - c_{w,i}A_i w_i - c_{A,i}A_i + \sum_r \left(P_{w,r}s_{i,r} - P_{w,r}b_{i,r} - tc_{i,r}(b_{i,r})\right) + \lambda_i\left(\bar{W}_i + \sum_r b_{i,r} - w_i A_i + \sum_r s_{i,r}\right) + \delta_i(\bar{A}_i - A_i)$$

(2)

where λ_i is the value of relaxing the constraint on water available to the producer by one unit and δ_i is the value of relaxing the constraint on land use by one unit. Both represent the producer's willingness to pay for an additional unit of water and land, respectively. The solutions to this problem are $w_i^*, A_i^*, s_{i,r}^*, b_{i,r}^*, \lambda_i^*$, and δ_i^* and satisfy the following first order conditions:

$$
\begin{aligned}
&\frac{\partial L_i}{\partial w_i} = P_y F_w(w_i, A_i) - c_{w,i} A_i - A_i \lambda_i \leq 0 && \text{c.s. } w_i \geq 0 \\
&\frac{\partial L_i}{\partial A_i} = P_y F_A(w_i, A_i) - c_{w,i} w_i - c_{A,i} - \lambda_i w_i - \delta_i \leq 0 && \text{c.s. A}_i \geq 0 \\
&\frac{\partial L_i}{\partial s_{i,r}} = P_w - \lambda_i \leq 0 && \text{c.s. s}_{i,r} \geq 0 \\
&\frac{\partial L_i}{\partial b_{i.,r}} = -P_w - tc(b_{i,r}) + \lambda_i \leq 0 && \text{c.s. b}_{i,r} \geq 0 \\
&\frac{\partial L_i}{\partial \lambda_i} = \bar{W}_i + \sum_r b_{i,r} - w_i A_i + \sum_r s_{i,r} \geq 0 && \text{c.s. } \lambda_i \geq 0 \\
&\frac{\partial L_i}{\partial \delta_i} = \bar{A}_i - A_i \geq 0 && \text{c.s. } \delta_i \geq 0
\end{aligned}
\tag{3}
$$

At least six of these conditions hold with equality, which six depend on the functional form and the model parameters. Without significant loss of generality, Table 1 identifies the conditions under which a producer would choose to sell, buy, or choose to not participate in the market. If a producer chooses to sell their water, $s_i > 0; b_i = 0$, then the price of water is equal to the marginal value of relaxing the constraint on water by one unit. If on the other hand, the producer chooses to buy water, $s_i = 0; b_i > 0$, then the price of water on the water market plus transaction costs incurred is equal to the marginal value of relaxing the constraint on water by one unit. Lastly, if the producer chooses not to participate in the water market, $s_i = 0; b_i = 0$, both the price of water of the market and the price plus transaction costs incurred are less than the marginal value of relaxing the constraint on water by one unit; the producer is better off using all of their water in production.

Table 1. Conditions under which a producer would choose to sell, buy, or choose not to participate in the market

Variable	Condition
$s_i > 0; b_i = 0$	$P_w = \lambda_i$
$s_i = 0; b_i > 0$	$P_w + tc(b_{i,r}) = \lambda_i$
$s_i = 0; b_i = 0$	$P_w < \lambda_i$ $P_w + tc(b_{i,r}) < \lambda_i$

The first condition states that if a positive amount of water is used in production, producer *i* will use water up to the point where the marginal profit from water in production divided by acres equals the marginal value of relaxing the constraint on water (i.e. the price of water on the market plus transaction costs) and sell all remaining water.

$$\begin{aligned} &\left[P_y F_w(w_i, A_i) - c_{w,i} A_i\right] / A_i = \lambda_i \\ &P_w + tc(b_{i,r}) = \lambda_i \\ &\Rightarrow \left[P_y F_w(w_i, A_i) - c_{w,i} A_i\right] / A_i = P_w + tc(b_{i,r}) \end{aligned} \tag{4}$$

If, on the other hand, producer *i* chooses not to sell, or $s_i^* = 0$, the following is true:

$$\begin{aligned} &\left[P_y F_w(w_i, A_i) - c_w A_i\right] / A_i = \lambda_i \\ &\lambda_i > P_w \\ &\Rightarrow \left[P_y F_w(w_i, A_i) - c_w A_i\right] / A_i > P_w \end{aligned} \tag{5}$$

The marginal profit from crop production is greater than the price of water; the producer is better off using water in production than selling water on the market.

The second condition states that if a positive amount of acres are used, producer *i* will use acres up to the point where the marginal profit from acres minus the per acre cost of using water is equal to the marginal value of relaxing the constraint on acres by one unit plus the price of water on the market times water use per acre. If zero acres are used, then the marginal profit from acres is less than the marginal value of relaxing the constraint on acres plus the price of water on the market times water use per acre by one unit.

The third condition states that if a positive amount of water is sold on the market, the marginal value of relaxing the constraint on water use by one unit is equal to the price of water on the market. If no water is sold on the market, the price of water is greater than the marginal revenue product of water. The fourth condition states that if a positive amount of water is bought on the market, the marginal value of relaxing the constraint on water use by one unit is equal to the price of water plus transaction costs incurred. If no water is purchased, the price of water is greater than the marginal revenue product of water plus transaction costs. If transaction costs are positive, there is a range of prices where no water is bought or sold but the price of water is greater than zero.

The fifth condition states that if the constraint on water use is binding, the initial endowment of water plus the amount purchased will be equal to the amount of water used in production minus the amount sold on the market. If the constraint is not binding, there is more water available than demanded, no water will be traded on the market and the price of water will be zero. The last condition states that if the constraint on acres is binding then the amount of acres used in production will be equal to the endowment of acres; if not, then fewer acres will be used than endowed and the marginal value of relaxing the constraint on acres, delta, is zero.

2.2.2 Municipal and Industrial Problem

The M&I problem is modeled as follows:[6]

$$
\begin{aligned}
&\min_{b_i} \quad C_i = \sum_r P_{w,r} b_{i,r} + \sum_r tc_{i,r}(b_{i,r}) \\
&s.t. \\
&\qquad b_{i,r} \geq 0 \\
&\qquad d_i \leq \bar{W}_i + \theta \sum_r b_{i,r}
\end{aligned} \tag{6}
$$

where d_i is the projected demand for water for M&I firm *i* given current water use and population projections and $0 < \theta \leq 1$ characterizing the firm yield of water purchased from regional pool r percentage of an average diversion that is considered firm yield. d_i , θ and $tc_{i,r}$ are exogenously determined while $P_{w,r}$ and $b_{i,r}$ are endogenously determined.

Resulting in the following Lagrangian:

$$L_i = \sum_r P_{w,r} b_{i,r} + \sum_r tc_{i,r}(b_{i,r}) + \lambda_i (\bar{W}_i + \theta \sum_r b_{i,r} - d_i) \tag{7}$$

The solutions to this problem are $b^*_{i.r}$ and λ^*_i and satisfy the following first order conditions:

$$
\begin{aligned}
&\frac{\partial L_i}{\partial b_{i,r}} = P_w + tc_b(b_{i,r}) + \lambda_i \theta \geq 0 \qquad && \text{c.s. } b_{i,r} \geq 0 \\
&\frac{\partial L_i}{\partial \lambda_i} = \bar{W}_i + \theta \sum_r b_{i,r} - d_i \geq 0 \qquad && \text{c.s.} \lambda_i \leq 0
\end{aligned} \tag{8}
$$

Lambda is how overall costs change as firms are given more water. As firms receive more water, overall costs go down resulting in lambda having a negative value. The M&I firm buys water such that, so long as $b^*_i > 0$, the price of water is positive, and the M&I firm's endowment is less than forecasted demands, $P_w + tc(b_{i,r}) = -\lambda_i \theta$. The firm will buy enough water to meet the firm

[6] Similar to producers, M&I agents purchase the consumptive use portion of their future demand.

yield of their future demand for water, equaling the price of water plus transaction costs incurred. Assuming the constraint is binding, the total amount of water purchased by the firm can be calculated as $\sum_r b_{i,r} = \frac{d_i - \overline{W}_i}{\theta}$.

2.2.3 Market Setting

Producers can buy water from other producers, sell water to other producers, or sell water to M&I firms. M&I firms can only buy water from producers. This is consistent with the empirical research that finds municipalities rarely sell water rights (Howe and Goemans, 2003; Brookshire, Granderton, Colby, 2004). Water is sold into a regional pool and purchased from a regional pool, rather than traded directly between firms. There is a market clearing price for each regional pool which is determined by the total amount of water bought out of and sold into and that regional pool.

The equilibrium is defined by the level of output, quantity of water traded, and price of water that results when producers seek to maximize their individual profits by choosing the amount of water to use in production, amount of land to use in production, and the amount of water to buy/sell, while at the same time M&I seeks to minimize their individual costs of meeting future demand for water (i.e., $w_i^*, A_i^*, s_{i,r}^*, b_{i,r}^*, \lambda_i^*$, and δ_i^*). Firms optimize according to their own idiosyncratic production/cost functions. The welfare for producer firms will be measured as the profit for each producer, based on output price, output quantity, cost of output and cost of water, price of water plus transaction costs incurred, and the quantity of water traded. Welfare for M&I firms will be measured as the total cost incurred by the water provider, based on price of water plus transaction costs incurred and quantity of water traded. In equilibrium, the amount of water that is purchased by all firms is equal to the amount of water sold.

The market clearing condition for each regional pool, *r*, is defined by:

$$\sum_i b_{i,r} = \sum_i s_{i,r} \qquad (9)$$

When the market clears, the total amount of water sold into a regional pool equals the total amount of water bought from the regional pool. Interactions between the firms in the water market determine the market clearing price of water in each regional pool. As a result of transaction costs, it may be true the market does not clear.

2.2.4 Example of a Water Market with Two Regions and Two Types of Firms

Figure 2 illustrates a two-region example, one relatively water "rich" and one relatively water "poor". In this example, each region consists of one producer and one M&I firm. When transaction costs are zero, there is essentially one large market for water, buyers and sellers do not care from which regional pool they purchase water. M&I buys the quantity of water necessary to meet their future demand for water and producer firms sell water up to the point where the marginal value of water in production is equal to the price of water on the market. There is one price of water and the quantity of water bought/sold is a total of all regions. To illustrate the impact of transaction costs on the market equilibrium, consider the case where producers do not buy water, only M&I buys water.

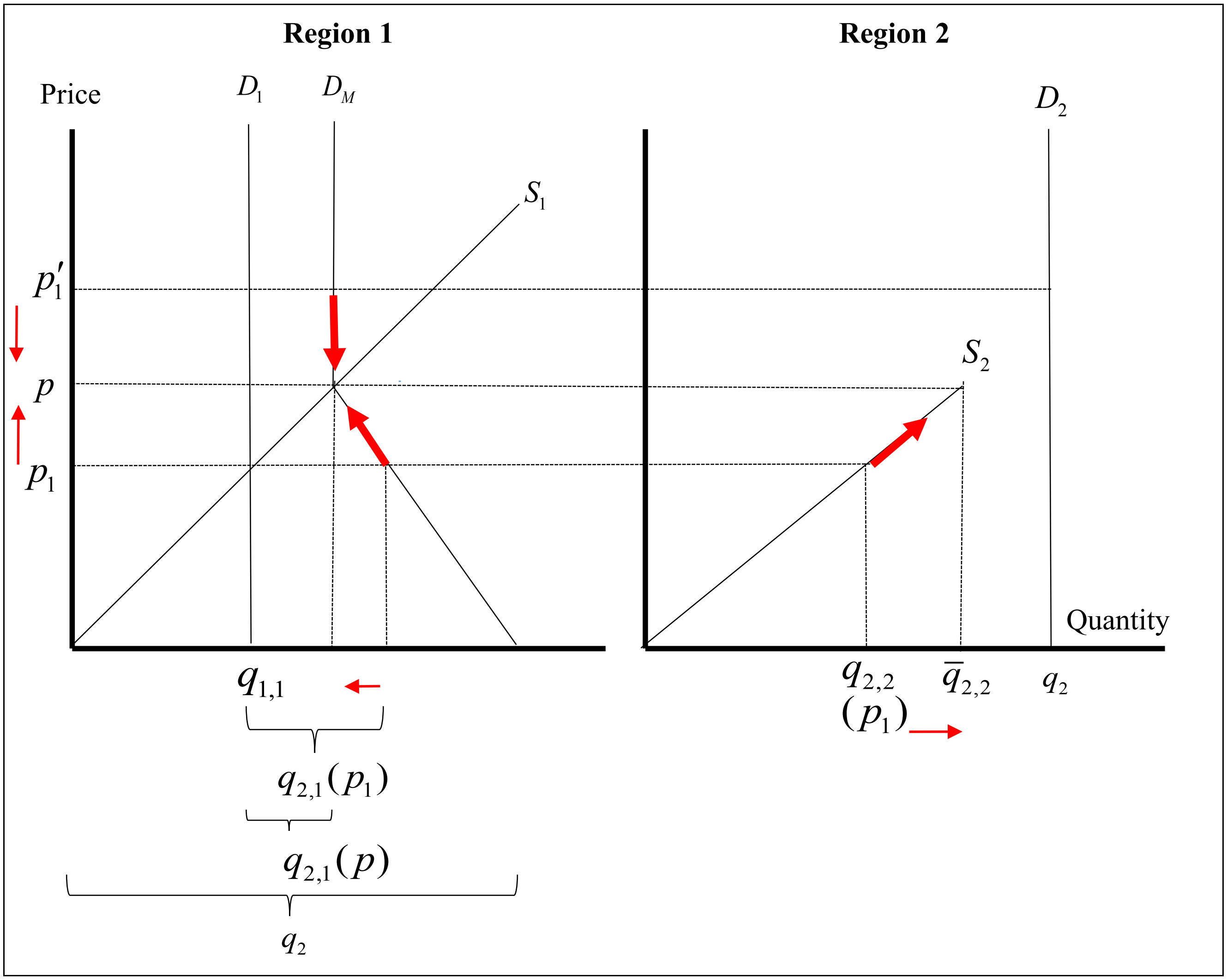


Figure 2. Equilibrium price and quantity in a market with two regional pools when transaction costs equal zero

In this example, the demand for water in region one, D_1, can be met by the supply in region one, S_1, resulting in the quantity demanded by Region 1 for water in Regional Pool 1 of $q_{1,1}$. The demand for water in region two, D_2, cannot be met by the supply in region two, S_2, so the M&I firm in Region 1 purchases water from Regional Pool 1 and Regional Pool 2, where the amount of water purchased from each regional pool depends on the price of water, generating the market demand curve, $D_M = D_1 + q_2 - q_{2,2}(p_1)$. Where q_2 is the total demand for water by Region 2 and $q_{2,2}(p_1)$ is the quantity demanded from Regional Pool 2 by Region 2 given the price of water in Region 1, p_1; the difference, $q_{2,1}(p_1)$, is the quantity demanded for water in Regional Pool 1 by Region 2 give the price of water in Region 1.

When transaction costs are zero, the buyer is indifferent to the regional pool from which they purchase water. The maximum amount of water the M&I firm in region two can purchase from region two is $\overline{q}_{2,2}$. If $p_1 < p$ then the M&I firm in region two is better off buying some water from Regional Pool 1, as it is cheaper than Regional Pool 2, and the remainder from Regional Pool 2. The M&I firm in Region 2 will buy $q_{2,2}(p_1)$ from Regional Pool 2 and $q_{2,1}(p_1) = q_2 - q_{2,2}(p_1)$ from Regional Pool 1.

The increased demand in Region 1 will increase the price of water in Regional Pool 1. Now that the price of water is higher in Regional Pool 1, the M&I firm in Region 2 chooses to purchase a larger portion of water from Regional Pool 2 and a smaller portion from Regional Pool 1. This causes the price of water to go up in Regional Pool 2, compared to Regional Pool 1. These dynamics continue until the price of water reaches p, at which point Region 1 will purchase $q_{1,1}$ from Regional Pool 1, and Region 2 will purchase $\overline{q}_{2,2}$ from Regional Pool 2 and $q_{2,1}(p) = q_2 - \overline{q}_{2,2}$ from Regional Pool 1. If $p_1' > p$, the price of water is higher than the willingness to pay of firms in both regions. The excess supply will cause the price to decrease until it reaches the market equilibrium price, p.

Now, the impact of transaction costs on the market equilibrium are discussed. Positive transaction costs segment the water market into regional pools, where the price of water differs across regional pools depending on transaction costs. Firms can buy from both regional pools; they incur institutional and physical transaction costs when buying from the regional pool were they are not located and only incur institutional transaction costs when they buy from their own regional pool. Assume institutional transaction costs are zero in order to simplify the graphical representation of the market dynamics and only physical transaction costs are positive.

Transaction costs shift the market demand curve outward for all points below p to $D_M{}^{tc}$ (see Figure 3). Because M&I demand is perfectly inelastic, transaction costs do not impact the quantity demanded by Region 2 from each regional pool when $p_1 > p$. Now that water is more expensive to purchase from outside one's own regional pool, the price at which the M&I firm in Region 2 switches from buying from Regional Pool 1 to Regional Pool 2 is now lower. When the price of water in Regional Pool 1 is p_1, to purchase water from Regional Pool 1, firms in Region 2 must pay $p_1 + tc_{2,1}$ (where $tc_{2,1}$ is the transaction costs in incurred when Region 2 purchases from Regional Pool 1); they purchase more water from their own regional pool and less water from Regional Pool 1, compared to the case without transaction costs.

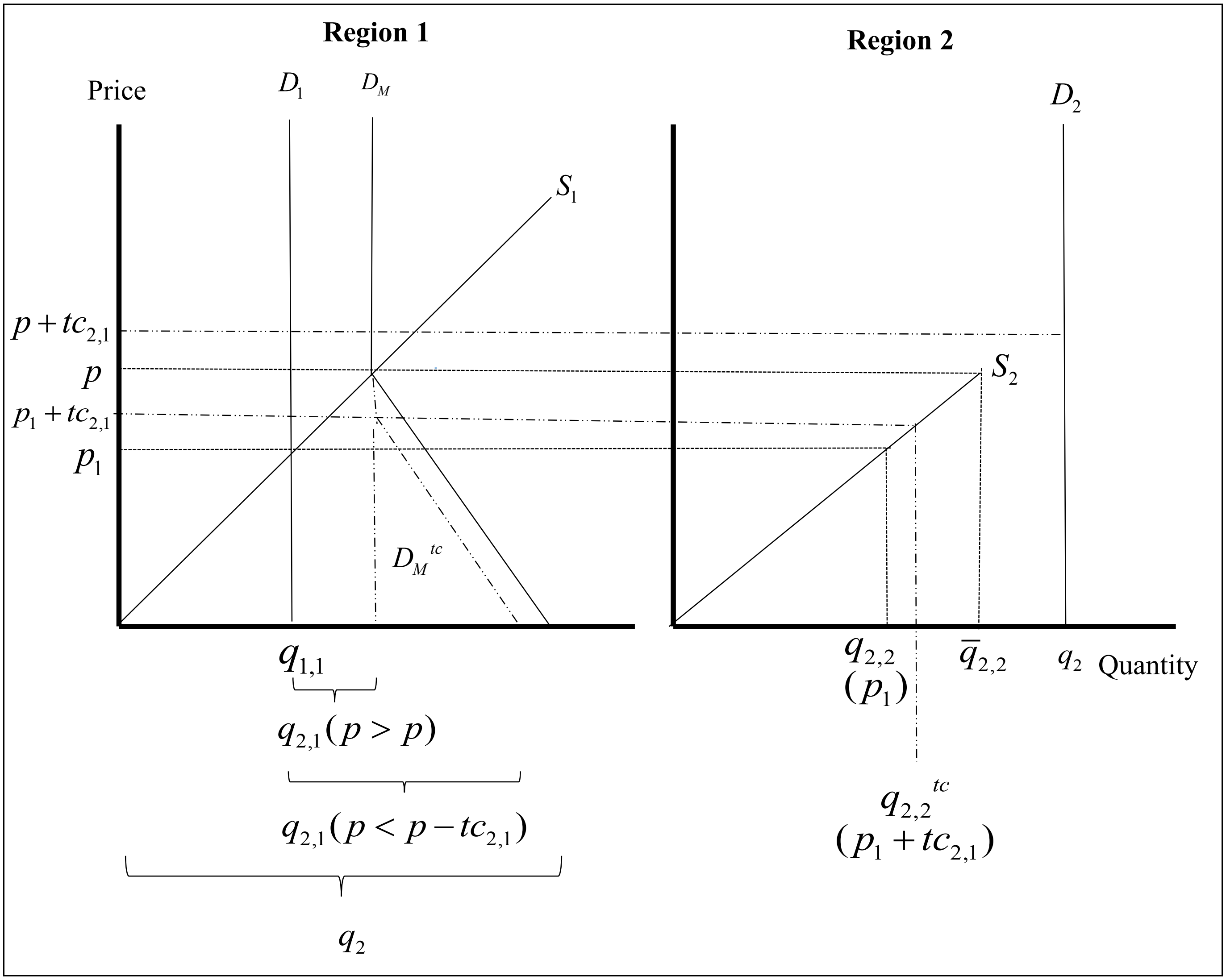


Figure 3. Equilibrium price and quantity in a market with two regional pools with positive transaction costs

Once $p_1 + tc_{2,1} \geq p$ the M&I firm in region two will want to purchase all of the available water from their regional pool, $\bar{q}_{2,2}$. All remaining water, $q_2 - \bar{q}_{2,2}$, will be purchased from Regional Pool 1 at the price in Regional Pool 1 plus transaction costs, $p_1 + tc_{2,1}$. Compared to the case without transaction costs, the point at which this shift occurs is at a lower price. Because the firms in Region 1 are willing to pay $p_1 + tc_{2,1}$ for water in Regional Pool 1, the price of water in

Regional Pool 2 is $p_2 = p_1 + tc_{2,1}$; there is now a wedge between the price of water in Regional Pool 1 and Regional Pool 2.

At $p_1 + tc_{2,1} < p$, the portion of the transaction cost borne by the buyer and seller depends on the relative elasticities the supply and demand curves. However, at $p_1 + tc_{2,1} \geq p$, the entire cost of the transaction cost is borne by the buyer; the M&I firm in Region 2 must purchase at least $q_2 - \overline{q}_{2,2}$ from Regional Pool 1 regardless of how much it costs and thus bears the entire cost. While the M&I firms bear the cost, the producer firms in Region 2 see a benefit from transaction costs as they can now charge a higher price for selling water, increasing from $p_2 = p_1$ to $p_2 = p_1 + tc_{2,1}$. The results described above will change based on the relative supply and demand in each region. In general, the producers in water poor regions will benefit from transaction costs as they increase the price of water on the water market. Whereas, producers in water rich regions do not necessarily benefit from transaction costs as the price of water in their region is less impacted by transaction costs.

2.3 Model Parameterization and Calibration

Numerical model simulation, based on data from the South Platte River in Colorado, is used to compare welfare outcomes for agricultural producers and municipal water consumers in the region under various population growth and climate change scenarios. The South Platte River Basin has one of the fastest growing populations in Colorado and faces significant water allocation challenges. This numerical simulation will provide policy makers with a better understanding of welfare outcomes associated with potential policy changes, including the reduction of transaction costs.

I use the software, General Algebraic Modeling System (GAMS), to solve the water market model, as described in the previous section, using the Extended Mathematical

Programming (EMP) framework and JAMS solver to declare and the subsolver PATH to solve the model presented above. Following Britz, Ferris, and Kuhn (2013), I characterize the problem as a Multiple Optimization Problems with Equilibrium Constraints (MOPEC) model, which allows me to model both the optimization problems of individual firms as well as how those actions affect the parameters of the market.

The EMP framework takes the optimization problem, automatically generates the first order conditions, and then uses the PATH solver to find a solution (Ferris, et al., 2009). The other option typically utilized to solve similar models is to formulate the problem as a mixed complementarity problem (MCP) and solve with the PATH solver. In this approach, the user must calculate and enter the Kuhn-Tucker conditions by hand. This process is more time consuming and prone to error compared to using EMP, particularly in large, non-linear settings (Britz, Ferris, & Kuhn, 2013).

2.3.1 Model Parameterization

I utilize secondary data as well as data from climate and crop models to parameterize the model to represent the South Platte River Basin in Colorado. The basin is divided into five regions and firms are located in one of these five regions. The North region consists of Boulder, Broomfield, and Larimer counties and is characterized by having both agricultural and M&I firms and access to water from the Colorado Big Thomson Project (CB-T), a water market with homogenous water shares and low transaction costs. The North Central region is Weld County and is characterized by having a very strong agricultural presence but also M&I.

The Central region includes Adams, Arapahoe, Clear Creek, Denver, Gilpin, and Jefferson counties and is characterized by large M&I firms and some agricultural firms. The South Metro region includes Douglas, Elbert, and Park and is characterized by M&I firms that utilize ground water and no agricultural producers[7]. The East is the final region and includes Morgan, Logan, Sedgwick, and Washington and is characterized by having only agricultural firms (Figure 4).

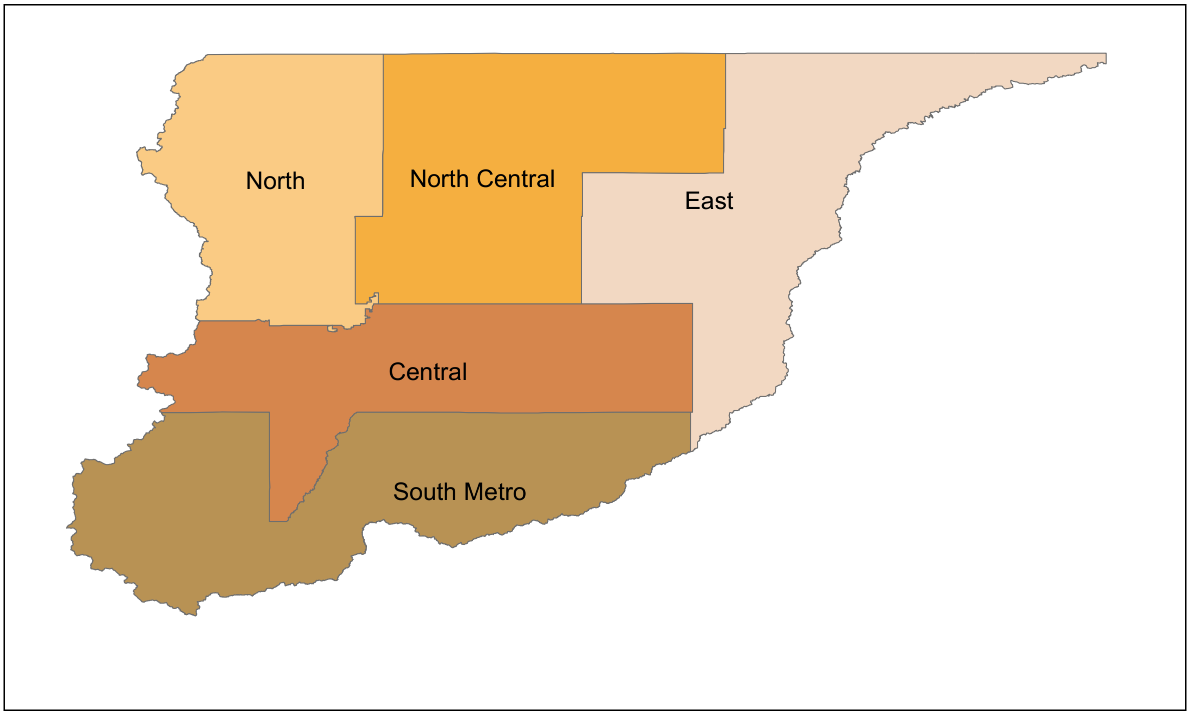


Figure 4. Map of the South Platte River Basin Divided into Five Regions

In the South Platte River Basin, there are four main irrigated crops produced: corn, hay/grass pasture, sugar beets and winter wheat. These four crops account for 92% of the total agricultural acres in the basin. The remaining crop types grown in the basin include dry beans, orchard, sod, and vegetables (Division 1 Irrigated Lands 2005, 2015). Hay and grass pasture (49% of total acres) are not included in this model. Price and cost data for alfalfa in the region are available, but not for other types of hay or grass pasture, hay and grass pasture are not irrigated every year, and can be sold on the commodity market or used as an input for livestock. Additionally, because of relatively high transportation costs, the market for hay is more localized

[7] There are a small number of producers in this region, but mostly produce grass pasture and are therefore not included in this model.

than other commodity crops that sell on the global market (e.g., corn, sugar beets, wheat) and thus acres/water are more likely to remain in hay in the face of population growth.

For the reasons listed here, I chose not to include either grass pasture or alfalfa in my model. The crops included in my model are irrigated corn, sugar beets and wheat and account for 43% of total acres in the South Platte River Basin. When I calculate demand for water given population growth, I do not decrease water demand by the portion of acres not included in my model, instead I assume that water will remain in grass pasture, alfalfa, and other acres. For example, in the 2011 drought in southern Colorado, the price of hay increased by roughly 50% in 2011 relative to 2010 (Bauman, Goemans, Pritchett, & Thilmany McFadden, 2013). The price of hay relative to other crops will be such that acres are likely to remain in hay and come out of other, less profitable crops.

Producer data is characterized at the regional level. There is one producer for each crop in each region for a total of 15 producers. Each producer is endowed acres based on the number of acres in production for each crop in each region in 2005 (Division 1 Irrigated Lands 2005, 2015). Producers are endowed with water based on the average diversions for each crop in each region from 1950-2014 (Colorado Division of Water Resources, 2016). Annual surface water diversions to agriculture from 1950-2014 in the South Platte River Basin are shown in Figure 5.

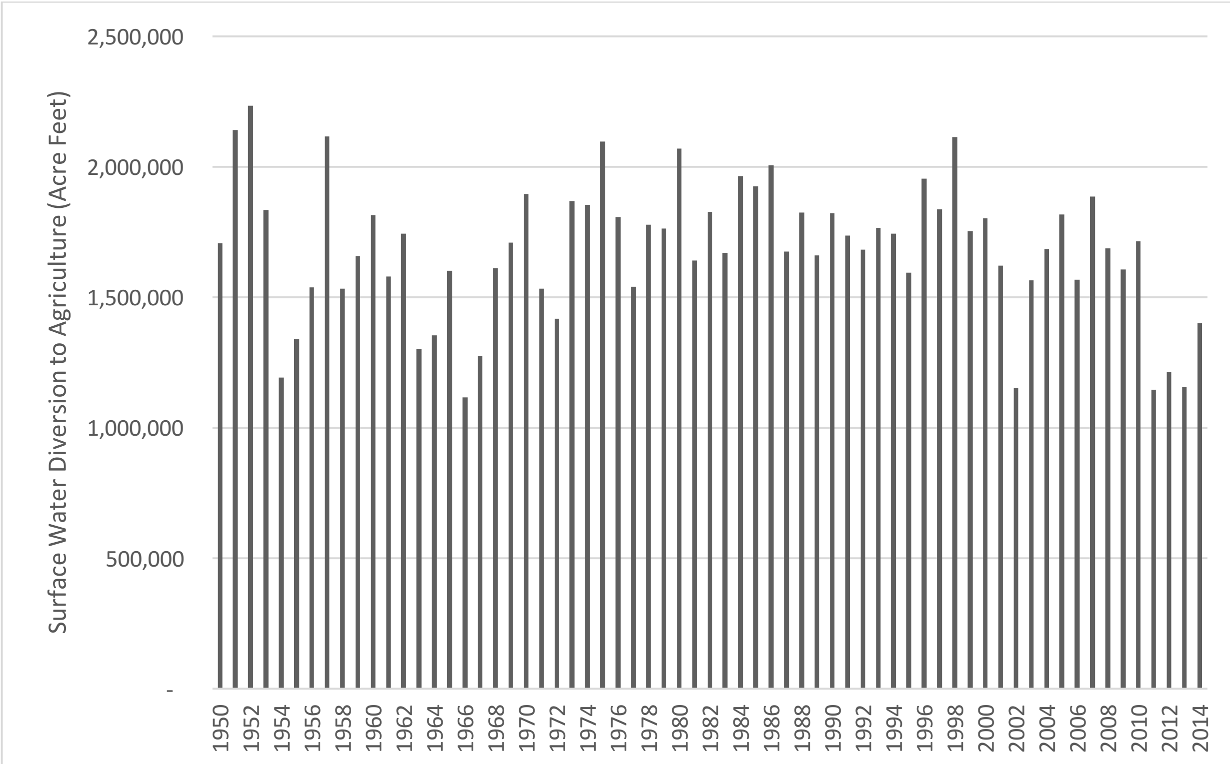


Figure 5. Annual Surface Water Diversion to Agriculture in the South Platte River Basin, CO from 1950-2014

Diversion data is based on the amount of water diverted through each diversion structure and therefore does not allocate water to each crop. To allocate diversions to each producer in the model, first, I decrease total diversions by the percentage of acres in the basin that are not included in my model. This assumes all crops use the same amount of water and was made due to lack of available data on water use for dry beans, grass pasture, orchard, sod, and vegetables. Second, I use acreage data and crop water use data to allocate regional diversions to each crop in my model within each region, shown in Table 2.

Table 2. Irrigated acres by crop and region

	North	North Central	Central	South Metro	East
Corn	83,949	63,920	18,196	0	61,441
Sugar beets	10,851	4,490	1,893	0	3,915
Wheat	21,490	4,269	6,541	0	8,804

Source: (Division 1 Irrigated Lands 2005, 2015)

Note that acres are allocated to each region based on where the water is diverted, which may or may not be the same region in which the acres are located. When water is transferred between users, the relevant information for the water market is where the water is diverted, not where it is used. For this reason, if the region in which water is diverted and used differs, the location of acres is not converted from where the water is diverted to where it is used. North and North Central are the main regions in which this is evident. Due to its upstream location, water is diverted in North but used in North Central or other downstream regions. Irrigated acres located in North are higher than in reality, whereas irrigated acres in North Central are lower.

When a producer sells his water right, he sells only the consumptive use portion of the water right. The portion of average diversions that are consumptively used is assumed to be the same across all firms and calculated based on delivery and application efficiency, where application efficiency depends on the type of irrigation utilized. In the study area, 85% of acres use flood irrigation and 15% use sprinkler irrigation (Division 1 Irrigated Lands 2005, 2015). Delivery efficiency is assumed to be 80%, flood irrigation is assumed to be 60% efficient, and sprinkler irrigation is assumed to be 75% efficient (Waskom, Cardon, & Crookston, 1994). This results in consumptive use calculated by adjusting average diversions downward by 50%. The consumptive use portion of average diversions are shown in Table 3.

Table 3. Consumptive use portion of average diversions by crop and region (acre feet)

	North	North Central	Central	South Metro	East
Corn	75,865	72,486	22,128	0	44,329
Sugar beets	14,507	7,534	3,408	0	4,183
Wheat	13,977	3,488	5,727	0	4,575

Crop specific production functions are estimated for the dominant soil type in each county using data from DayCent, a crop model parameterized for the South Platte River Basin. The DayCent model is a widely used dynamic ecosystem model for cropland, forest, grassland and savanna (Parton, Hartman, Ojima, & Schimel, 1998). The major processes simulated are crop growth and production, soil water and solute transport, organic matter decomposition, and trace gas emissions. PRISM spatial climate datasets (PRISM Climate Group, 2015) were used as input to drive the model.

Soil property data were derived from the Soil Survey Geographic database (SSURGO) (USDA Natural Resource Conservation Service, 2009). Hydrologic response units (HRUs) were defined as the unique combination of climate, county, and soil within irrigated fields as delineated by the Colorado Water Conservation Board and Colorado Division of Water Resources (Division 1 Irrigation Lands, 2005; Colorado Division of Water Resources, 2016). A set of predefined dates and typical management strategies is used to model management practices at each HRU. The DayCent model was calibrated using the National Agricultural Statistics Service (NASS) reported yield (1980-2015) in Weld County (NASS Quick Stat 2.0, 2016). The water used by a crop is assumed to be the water at the root, or the water consumptively used by the plant.

Production functions are assumed to have the following form

$$F(w_i, A_i) = A_i^{\alpha} f_i(w_i) \tag{10}$$

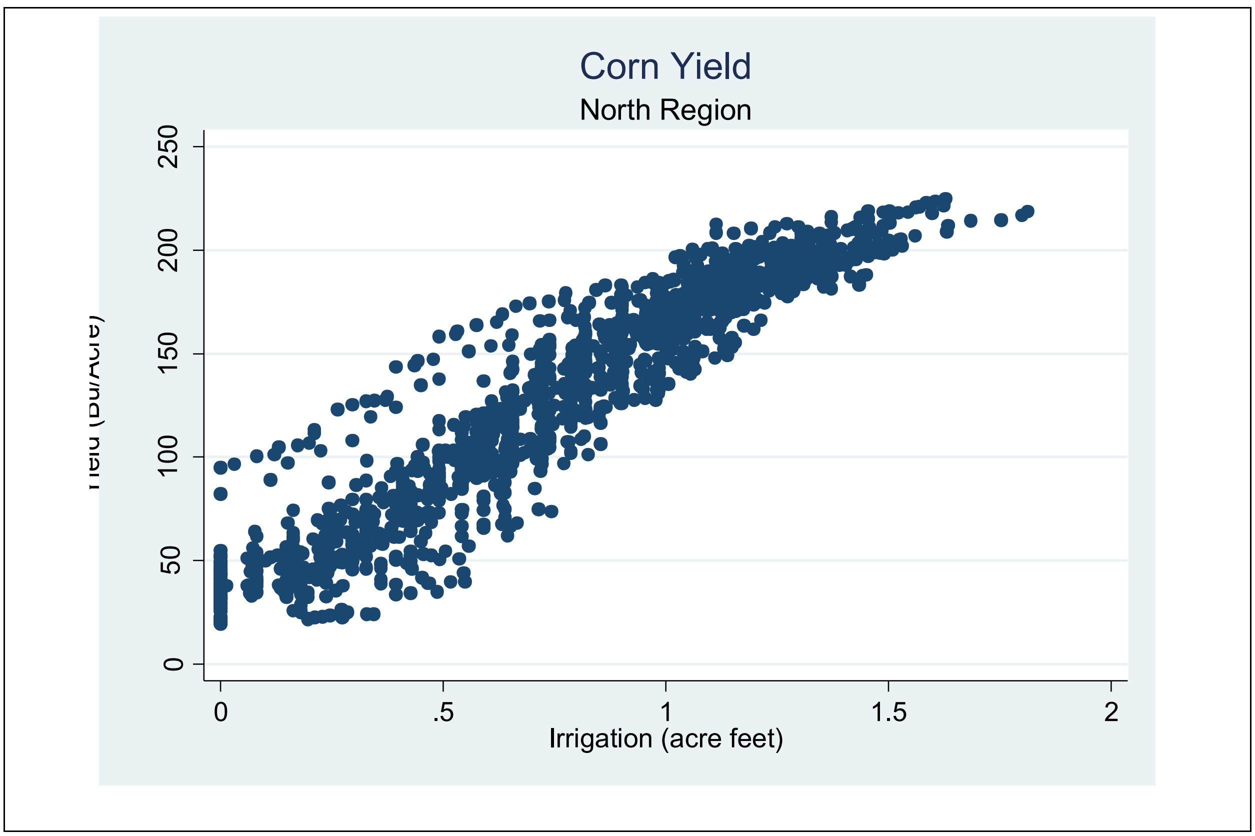
where per acre crop production functions are estimated assuming the following functional form

$$f_i(w_i) = \beta_{0,i} w_i^{\beta_{1,i}} \tag{11}$$

$\beta_{0,i}$ is the total factor productivity of water for firm *i* and $\beta_{1,i}$ is the output elasticity of water for firm *i*. The resulting econometric model that is estimated is

$$\ln(f_i(w_i)) = \ln(\beta_{0,i}) + \beta_{1,i} \ln(w_i) \tag{12}$$

For the production function to be concave, $0 < \beta_{1,i} < 1$; estimates of $\beta_{1,i}$ range between 0.43 and 0.80. Selected DayCent crop yield data is presented in Figure 6.



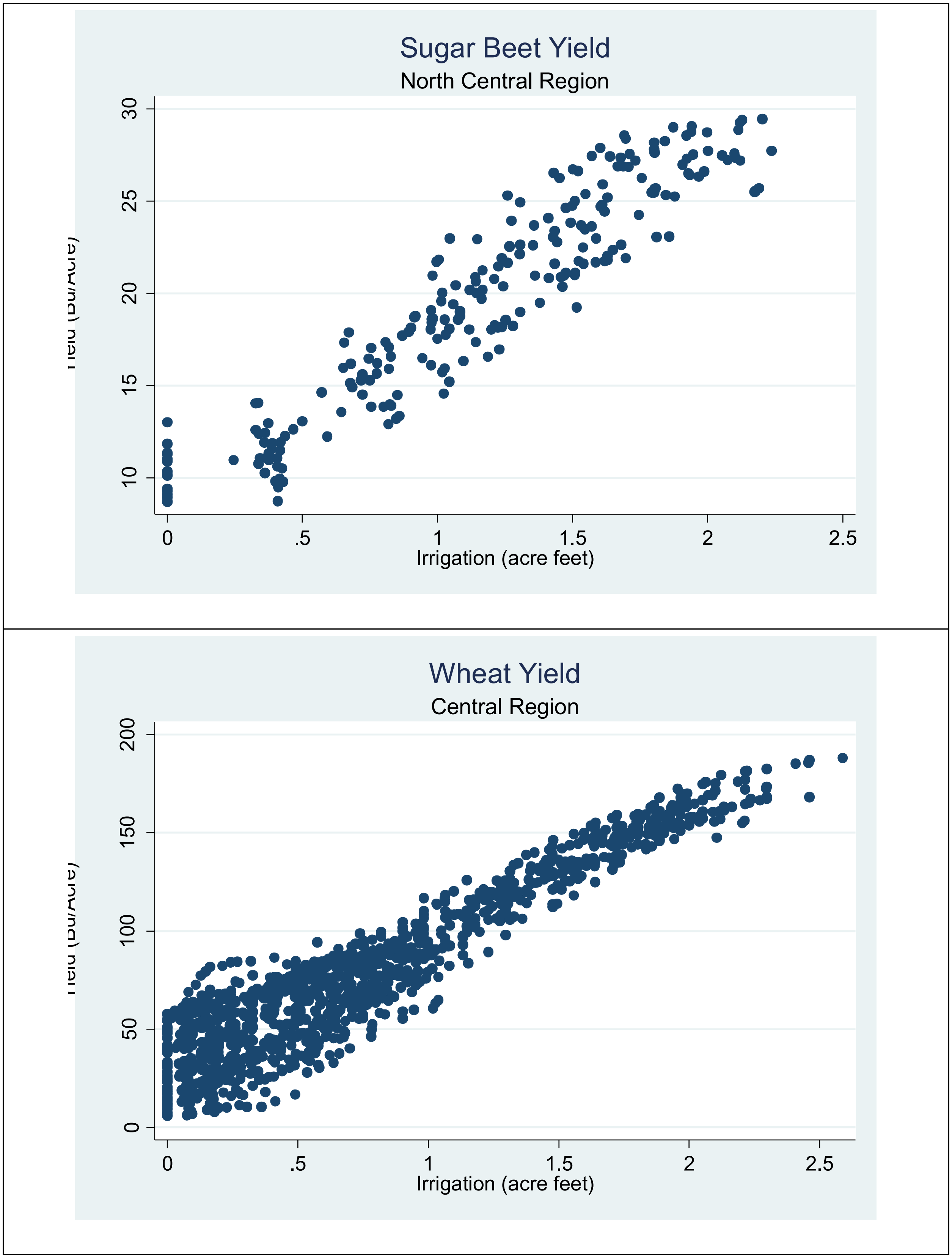


Figure 6. DayCent crop yield data for selected regions

The crop production function is estimated on a per acre basis. To reflect unobserved variability in the quality of land, I calibrate the following aggregate production function: $F_i(w_i, A_i) = A_i^{\alpha_i} \exp(\beta_{0,i}) w_i^{\beta_{1,i}}$ where $\beta_{0,i}$ and $\beta_{1,i}$ are estimated from DayCent. The exponent on acres, α_i is unknown based on the data and methods utilized to estimate production function parameters and is estimated during calibration.

Crop prices are an average of the past 5 years (2010-2015)[8] from National Agricultural Statistical Service (NASS) data (NASS Quick Stat 2.0, 2016). The cost of production per acre is the total direct costs of production, taken from the 2013 Colorado State Extension Crop Budgets for the South Platte Valley (Crop Enterprise Budgets, 2016). The cost of water is estimated based on the marginal cost of diverting one acre foot of water from a ditch to a field (add source). Output prices and costs are the same across regions (Table 4).

Table 4. Output cost by crop

	Output Price	**Output Cost**	**Cost of Water**
Corn	\$5.05 bushel/acre	\$655 per acre	\$15 per acre
Sugar beets	\$55 ton/acre	\$1,323 per acre	\$15 per acre
Wheat	\$6.2 bushel/acre	\$421 per acre	\$15 per acre

There is one M&I firm in each region. Data on M&I demand is taken from the 2010 Colorado Statewide Water Supply Initiative (SWSI), Appendix H (Statewide Water Supply Initiative-Appendix H, 2011). Most municipalities have some extra supplies of water, so current demand is likely to be an underestimate of actual water rights holdings, but is the most accurate estimate available. Future M&I demand is estimated for the long run (2040). Only the

[8] Price data for sugar beets in 2015 was not available through quick stats, so the price of sugar beets is an average of price from 2010-2014.

consumptive use portion of a water right is purchased by M&I, which is assumed to be 20% (Table 5). Note that future demand scenarios account for the current M&I water holdings assuming that municipalities will purchase the difference between their current demand for water and future demand for water on the water market.

Table 5. M&I Future Consumptive Use Water Demand (AFY)

Region	2050 medium
North	18,400
North Central	16,600
Central	44,300
South Metro	11,400
East	2,600

To meet future demand for water, M&I firms buy the firm yield of a water right, not the average diversion amount that is used by producers. The portion of average diversions considered firm yield are calculated based on the diversions in drought years divided by average diversions. The four years with the lowest diversions (1996, 2002, 2011, 2013) were divided by average diversions from 1950-2014, resulting in an average of 69%. The firm yield percentage of average diversions, 70%, is used in the model; for every one acre foot of water purchased, 0.7 acre feet of future demand is met.[9]

Table 6 describes the transaction costs associated with buying water, where the rows are the buyers and columns are the regional pools from which they are purchasing. The regional pools defined here line up with the previously defined regions with the exception of Region 1

[9] This is consistent with a recent agreement between municipalities located in the Central region in 2009 to acquire water, they agreed that the dry year consumptive use shall be no less than 60% of the average consumptive use (ACWWA, ACWWPID, ECVV, United, United ACWWA Enterprise, United Chambers Enterprise, 2009).

which includes two regional pools, one for native water (titled North) and one for Colorado Big Thompson (CBT) water. Legal restrictions on CBT water guarantee that it can only be sold within the North region, thus transaction costs are very low for firms in the North region to buy CBT water and prohibitively high for all other firms.

Table 6. Transaction costs associated with transferring water between regions

	North	**North Central**	**Central**	**East**	**CBT**
	Physical Transaction Costs				
North	$0	$20,000	$20,000	$30,000	$0
North Central	$10,000	$0	$20,000	$20,000	n/a
Central	$20,000	$20,000	$0	$20,000	n/a
South Metro[10]	$30,000	$30,000	$20,000	$20,000	n/a
East	$1,000	$1,000	$1,000	$0	n/a
	Legal Transaction Costs				
All regions	$5,000	$5,000	$5,000	$5,000	$5,000

Rows are buyers and columns are regional pool from which they are purchasing

Regions are defined with transaction costs in mind, where counties with similar water access are grouped together. The infrastructure/physical costs vary depending on the locations of the buyer and the regional pool from which they are purchasing. The institutional costs of transferring water are the same across regions. Due to lack of publically available data, transaction costs are estimated as a ballpark figure, based onmultiple sources.

Based on an interview with a water consulting firm with extensive knowledge of the transaction costs associated with transferring water in the South Platte River Basin, the market price of water in the basin is around $25,000. Transaction costs will be a portion of this total depending on the location of the buyer and seller, with the institutional portion of transaction costs accounting for around $5,000 (DiNatale, 2015). The only study I could find that directly

[10] Note that because there is no water in the South Metro region, transaction costs are only for the South Metro purchasing water from other regions.

estimated transaction costs found that the legal costs associated with transferring water in Colorado from 1980-1989 accounted for around 12% of the total price (Colby, 1990). Because transaction costs are contained in the price paid for water, price data, which is more readily available, is helpful for estimating transaction costs. In the data used by Basta and Colby (2010), the price of water transferred in Colorado from 1987-2007 ranged from $10,000 to $20,000 per acre foot. In a Colorado news article, shares of CBT water sold for $52,000 per acre foot in 2015 (Lynn, 2015).

In the data used by Payne, Smith and Landry (2014) on water transfers in the South Platte River Basin, prices range from $434 per acre foot to $25,556 per acre foot and average $7,417 per acre foot. Note that the difference in price paid by agricultural and municipal buyers was not statistically significantly different. In a 2009 agreement between a group of municipalities in the Central region to acquire water from the North Central region, the price paid for an acre foot of water was $22,000 and the additional infrastructure costs were $12,000 per acre foot (ACWWA, ACWWPID, ECVV, United, United ACWWA Enterprise, United Chambers Enterprise, 2009). Estimates of transaction costs in table five will serve as the base case scenario.

2.3.2 Model Calibration

The goal of calibration is to adjust parameters such that the model accurately predicts the current allocation of acres and water use among producers in the study area. Given the high cost of using an additional acre, the low cost of an additional unit of water, and the additional output generated by each additional acre foot of water, most producers want to use considerably more water per acre than one would see in reality. To ensure water use per acre is in a reasonable range, I set an upper bound on water use.

I explored three choices for the upper bound: one, the water use associated with the maximum yield for each crop in the DayCent data; two, the maximum water use for each crop in the DayCent data; and three, the consumptively used portion of the endowment per acre. Using the first two approaches, the majority of producers chose to use more water per acre than they are endowed and fewer acres than endowed. With the first two approaches, I am not able to calibrate water use and acres within reasonable bounds. Therefore, the last approach, limiting water per acre to be the consumptive use portion of the endowment per acre is utilized.

Output prices and output costs are adjusted so all crops are profitable at the consumptive use portion of the endowment per acre. Output prices are consistent across all regions, but output costs can vary, assuming the cost of production differs based on location. The output price of sugar beets is decreased by 15%, from $55 to $63.25. Output cost of corn in the in the East region is decreased by 5% from $654 to $622. Output cost of sugar beets in the North region is decreased by 5% from $1,323 to $1,257 and in the East region by 20% to $1,058. Output cost of wheat in the East region is decreased by 20% from $420 to $336.

In the production function $F_i(w_i, A_i) = A_i^{\alpha_i} \beta_{0,i} w_i^{\beta_{1,i}}$, $\beta_{0,i}$ and $\beta_{1,i}$ are estimated from per acre crop production data, but the exponent on acres, α_i is unknown based on the data and methods utilized to estimate production function parameters. I use the value of α_i, where $0 < \alpha_i < 1$, as a means by which to calibrate the model. For my model to accurately predict the current allocation of water and acres, producers must want to use their full endowment of acres and water and not want to sell any water.

The values for α_i are calculated such that the marginal profit from production is equal across all users at their profit maximization. Values range from 0.976 to 0.999 depending on the crop and region. Estimated values of α_i tell us that each additional acre is slightly less productive than the previous; producers will choose to fully irrigate their most productive acres first. When the model is run with a upper bound on water use, adjusted prices and output costs, and estimated values of α_i, the model predicts acres and water use to be the same as what are currently used in the region.

When I evaluate the change in acres and water use in 2050, my model predicts irrigated acres and water use will decrease by 28% if I assume all “other acres” (dry beans, orchard, sod, and vegetables) come out of production. Water use will decrease by 20% if I assume “other acres” remain in production. Reality is likely somewhere between the two assumptions, where the high value crops will stay in production and the lower valued crops will not. For the same region and time period SWSI (2010) estimates a decrease in irrigated acres between 22% and 32% and based on an average decrease in acres, water use will decrease 27%.

To calibrate the price of water predicted in the model to reflect current conditions, I assume the profit earned from crop production is the present value of an annualized sum, with an interest rate of 3% and a time horizon of 50 years. When a producer sells his water right on the water market he receives a one-time payment and forfeits any future profits from crop production. Thus, when a producer is choosing between using water on his crops and selling water on the water market, he is actually comparing the value he will receive from a future stream of profits from crop production to that which he will receive from the water market. Calculating profit earned from crop production as the present value of an annualized sum allows for this comparison.

Currently in the South Platte River Basin, there is a wedge between the value of a future stream of profits from crop production and the price of water on the market. Producers make decisions based on the expected crop price and expected water price, rather than current prices. To account for this wedge, the value of production is increased by a factor such that the current price of water is reflected in the model.

2.3.4 Model Scenarios

To evaluate how the presence of transaction costs in water markets impact welfare outcomes, in terms of overall efficiency and distributional impacts, I focus on three results: (1) how much water is sold from producers to M&I firms and where those trades take place, (2) producer profits/revenues, (2) and M&I costs. These results are evaluated for four scenarios, the first scenario evaluates the impact of population growth under current institutional settings, serving as the base case. The remaining scenarios evaluate how transaction costs in water markets impact welfare outcomes. Lastly, I estimate how regional economies will change as a result of population growth, estimating impacts with and without transaction costs.

Scenarios include:

1. *Population growth (base)*. I evaluate the impact of population growth given the current institutional setting (i.e. the existence of transaction costs). This scenario will serve as the base from which other scenarios will be compared.
2. *Institutional transaction costs.* I evaluate the impact of institutional transactions costs, which are assumed to be homogenous across regions, demonstrating how impacts of population growth change depending on the level of institutional transaction costs. Impacts are evaluated as institutional transaction costs are decreased in 10% increments from 10% to 50% and then evaluated for zero institutional transaction costs.
3. *Physical transaction costs.* I evaluate the impact of physical transaction costs, assumed to be heterogeneous across regions, demonstrating how impacts of population growth

change depending on the level of physical transaction costs. Impacts are evaluated as physical transaction costs are decreased in 10% increments from 10% to 50% then evaluated for zero physical transaction costs.

4. *Physical and institutional transaction costs.* I evaluate the impact of population growth changes for varying levels of both physical and legal transaction costs, representing the most realistic characterization of transaction costs.

2.4 Results: Impacts of Transaction Costs

Results from the five scenarios evaluated in this chapter demonstrate that heterogeneous firms and the existence of both institutional and physical costs play a role in welfare outcomes from the water market, showing the importance of including transaction cost in a model of a water market to provide policy and market analysis.

2.4.1 Impacts of Population Growth

Water is sold from producers to M&I firms to meet forecasted demand for water as a result of population growth. Model results predict that irrigated acres used in production for the South Platte River Basin will decrease from 290,000 acres to 150,000 acres as a result of population growth, given current institutional settings, i.e., the existence of physical institutional transaction costs (Figure 7). North Central sees the largest decrease in irrigated acres (50,000), followed by North (35,000), Central (27,000), and East (25,000).

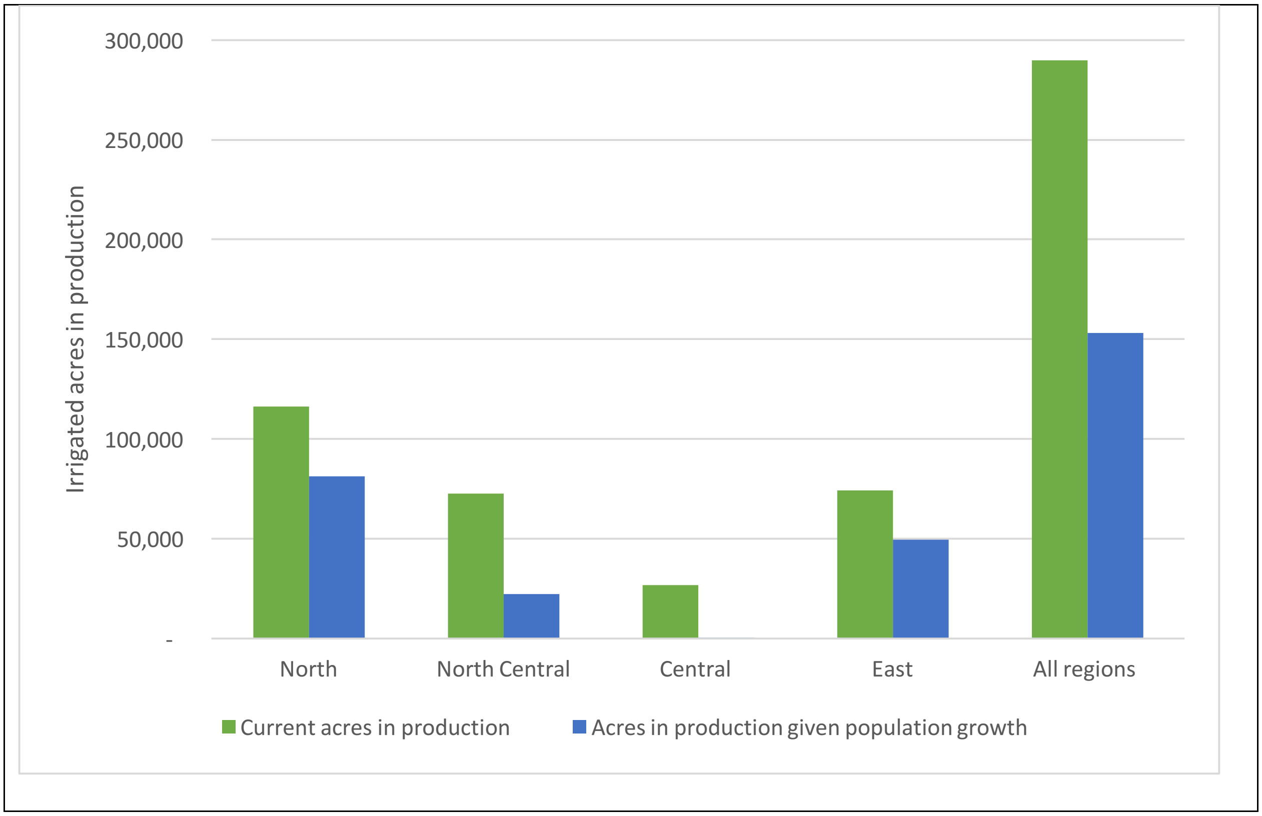
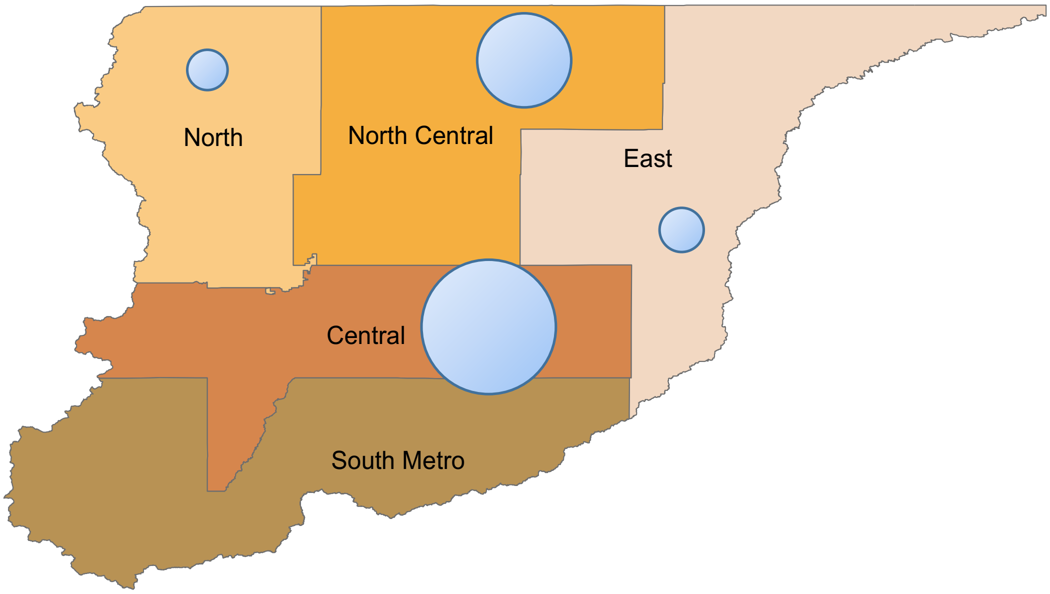


Figure 7. Change in acres resulting from population growth, given current institutional setting

In percentage terms, Central, a water poor region with high population growth, sees the largest decrease in irrigated acres, transferring 100% of irrigated acres out of agriculture in order to meet future demand for water (Figure 8). North Central, a water rich region conveniently located to Central, sees a 70% decrease in irrigated agriculture. North Central faces population growth pressures from within the region and, due to relatively low cost of transferring water also faces population growth pressures from outside regions.. Resulting in relatively large transfers of water out of agriculture compared to neighboring, water rich regions. East and North, both water rich regions, see a 30% and 33% decrease in irrigated acres, respectively.



	% change in irrigated acres
North	-30%
North Central	-70%
Central	-100%
East	-33%
All regions	**-47%**

Figure 8. Percent change in irrigated acres resulting from population growth, given current institutional settings

To demonstrate the impact of population growth on producer profit, I evaluate the two ways in which producers earn profits: by producing crops and by selling water rights on the water market. When a producer chooses between using water for production and selling it on the water market, he compares the value he will receive from a future stream of profits from crop production to that which he will receive from the one-time payment from the water market. In order to compare the two means by which producers earn profits, results are presented such that profits from crop production are the present value of a future stream of profits (assuming a 50 year time horizon and 3% interest rate) and profits from the water market are simply the amount of money received from the one-time payment associated with selling water.

To estimate the impact of population growth on producer profits, I assume current institutional settings comparing current profits to profits resulting from long run population growth. Assuming zero population growth, profit is earned from production of crops; the water market is in equilibrium and there is no buying and selling of water between producers or from M&I. As population increases and M&I firms purchase water to meet future demand, producers can now choose to either use water in production or sell water on the water market.

Comparing producer profit by region with zero population growth to profits with long run population growth, assuming current institutional settings, total producer profit across all regions increases with population growth, confirming previous research documenting the increase in producer welfare resulting from water markets (Booker & Young, 1994; Booker, Rosegrant et al., 2000; Michelsen & Ward, 2005). The present value of a future stream of profits earned from production decrease, but profits earned from selling water increase (Figure 9). Producer profits increase slightly North, North Central, and East (i.e., water rich regions), while Central, the region with the largest population growth and a small endowment of water, sees the largest increase in profit, shifting almost profit from production into profit from water sales.

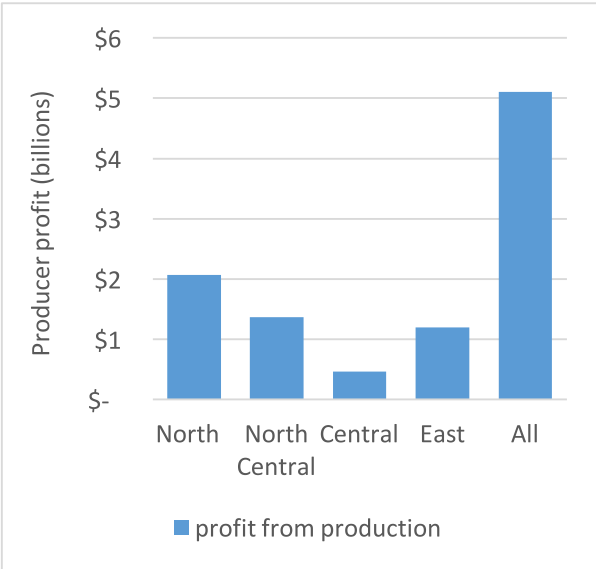
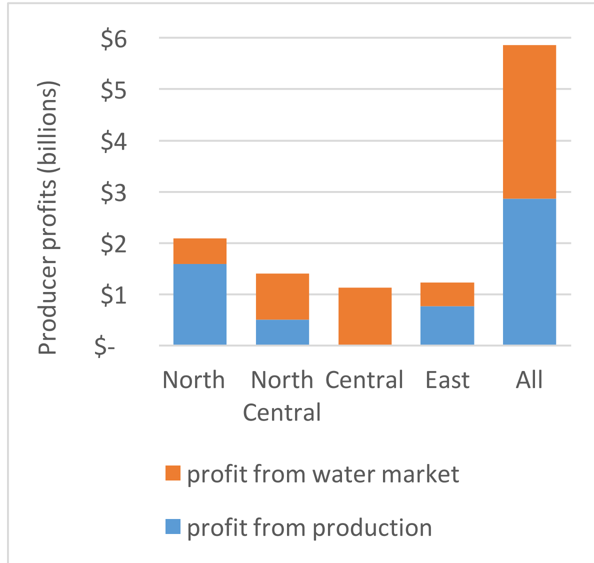
Producer profit without population growth	Producer profit with population growth
	

Figure 9. Producer profit[11] with and without population growth, assuming current institutional settings

The average cost per acre foot to acquire water in order to meet future demand for water in the South Platte River Basin is $34,700 ranging from $21,200 to $47,700 (Table 7). The two water scarce regions with high population growth, Central and South Metro have the highest cost per acre foot at $41,200 and $47,700, respectively. Both of these regions purchase water from outside regions and thus incur transaction costs, increasing the cost of acquiring water. Water rich regions, North, North Central and East spend less per acre foot to meet future demand, spending $24,100, 21,200 and $27,700 per acre foot, respectively.

[11] Producer profits earned from crop production are the present value of a future stream of profits and profits earned from the water market are a one-time payment

Table 7. Cost per acre foot for M&I to acquire water for future demand, given current institutional settings

Region	Cost per acre foot
North	$24,100
North Central	$21,200
Central	$41,200
South Metro	$47,700
East	$27,700
Average	$34,700

2.4.2 Impacts of Institutional Transaction Costs

Given the characterization of M&I demand as perfectly inelastic, a change in the cost to acquire water does not change the total amount of water purchased, but it can shift from which region water is purchased as well as the most profitable mix of acres and water chosen by the producer. In the case of institutional transaction costs, as a result of the homogeneity of the transaction cost, the allocation of acres across regions resulting from population growth comparing no transaction costs and 100% institutional transaction costs is virtually unchanged. Although institutional transaction costs increase the cost of purchasing water, they do not change the relative cost of purchasing water across regions. Thus, given the inelastic nature of M&I demand, the inclusion of homogeneous transaction costs do not change the allocation of acres in the face of population growth compared to the case without transaction costs.

Similarly, producer profits remain almost exactly the same as institutional transaction costs decrease from 100% to 0% (Table 8). Regional producer profits range from $600 million to $2 billion, with North earning the highest profits and Central earning the lowest. Central is the only region that sees a slight change in profits, increasing from $500 million to $600 million as institutional transaction costs are reduced to zero. When transaction costs are reduced to zero, producers enter the water market, in which some portion of water is purchased by high value producers in every region. This changes market dynamics slightly, leading to the small increase in profits in Central.

Producer profits remain almost the same as institutional transaction costs are decreased (Table 8) because the price of water received by the seller does not change, remaining at $19,000 per acre foot regardless of the region or size of the transaction costs. Because institutional transaction costs do not vary across regions, municipalities purchase water from any combination of regions up until the point where the marginal value of water is equated across all producers. The region from which water is purchased is driven by the relative marginal productivity of water in production in each region. When transaction costs are zero, there is essentially one large pool of water from which to purchase water, resulting in one price of water across all regions.

Table 8. Producer profits as institutional transaction costs are reduced (in billions)

Region	Full institutional transaction costs	No transaction costs
North	$2.1	$2.1
North Central	$1.6	$1.6
Central	$0.5	$0.6
East	$1.2	$1.2
Total	**$5.4**	**$5.5**

When governments have discussed decreasing transaction costs (e.g., Iseman et al., 2012), the discussion is typically centered on making it easier to transfer water between users from a legal standpoint. An interesting result from this research is that reducing transaction costs that do not vary across regions are likely to have a minimal impact on the functioning of a water market and the associated producer welfare outcomes until the price of water rights becomes high enough to deter development.

While the price of water does not vary across regions nor as institutional transaction costs decrease, the cost incurred by municipalities when purchasing water does vary (Table 9). As institutional transaction costs decrease, the cost for cities to acquire water decreases. Although the price paid for a water right remains the same, the total cost of purchasing a water right (i.e., the price of water plus transaction costs) decreases. Compared to the case with full institutional transaction costs, for each 10% reduction in institutional transaction costs, the cost for M&I to acquire water decreases by 2% for all regions. Municipalities, and therefore their customers, benefit from a reduction in institutional transaction costs. Cost per acre foot does not vary across regions; each region has access to water at the same cost as other regions, thus each M&I firm can reach the same minimum cost per acre foot to acquire water. Cost to acquire water, assuming full institutional transaction costs is $24,000 per acre foot across all regions and reduces to $19,000 when institutional transaction costs are reduced by 100%.

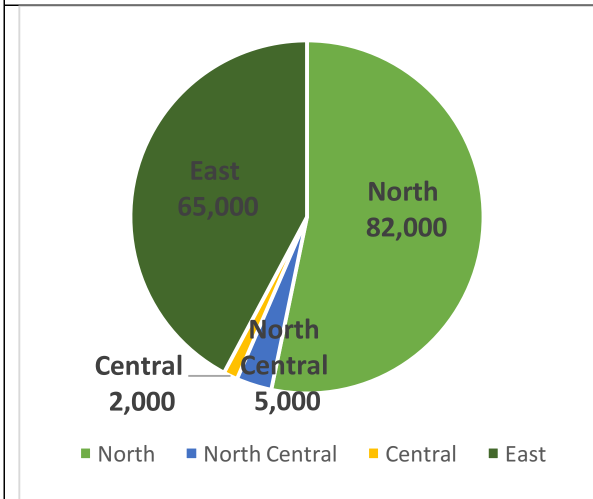
Table 9. Cost per acre foot for M&I to acquire water as institutional transaction costs decrease given long run population growth

Region	**100% Institutional transaction costs**	**10% decrease**	**20% decrease**	**30% decrease**	**40% decrease**	**50% decrease**	**No transaction costs**
All regions	$24,000	$24,000	$23,000	$23,000	$22,000	$22,00	$19,000

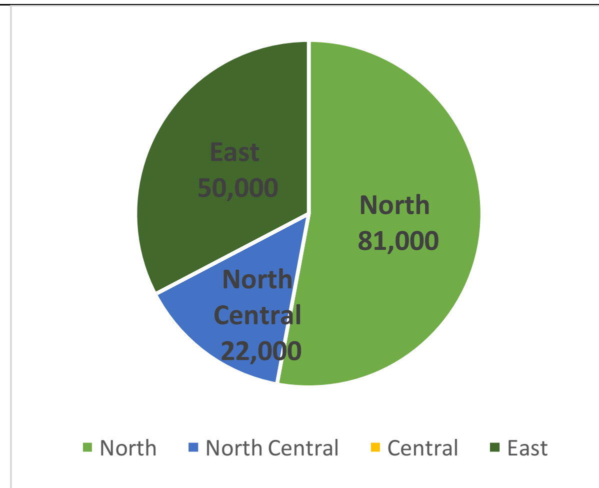
2.4.3 Impacts of Physical Transaction Costs

Physical transaction costs, assumed to vary by region, increase the cost for M&I firms to purchase water. Although this change in the cost to acquire water does not change the total amount of water purchased by M&I (given the characterization of M&I demand as perfectly inelastic), it does shift from which region water is purchased as well as the most profitable mix of acres and water chosen by the producer (Figure 10). Compared to the case without transaction costs, including physical transaction costs leads to 1,000 fewer overall acres, with the largest changes in allocation occurring in East and North Central. When physical transaction costs are introduced, East utilizes 15,000 fewer acres, 16,000 fewer acre feet of water in production and shifts from using 1.6 acre feet of water per acre to 1.2 when compared to the case with zero transaction costs. North Central utilizes 17,000 more acres, 20,000 more acre feet of water and water use per acre foot remains at 0.7. Although these changes in irrigated acres are relatively small compared to the total irrigated acres in the basin, this simulation shows that physical transaction costs do impact the number and, more significantly, the allocation of acres across the basin, even as M&I firms are characterized as having perfectly inelastic demand.

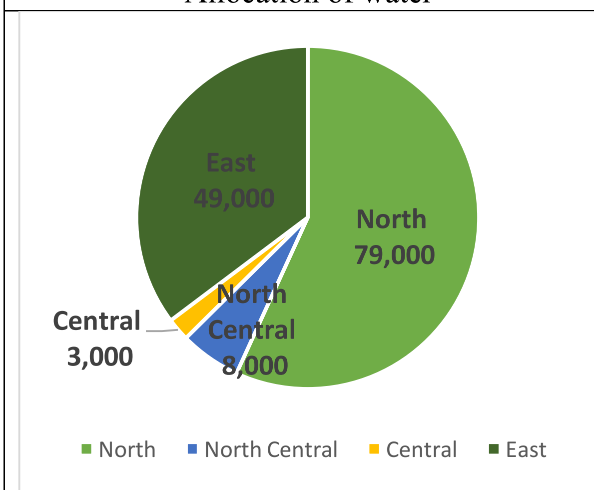
No transaction costs
Allocation of acres



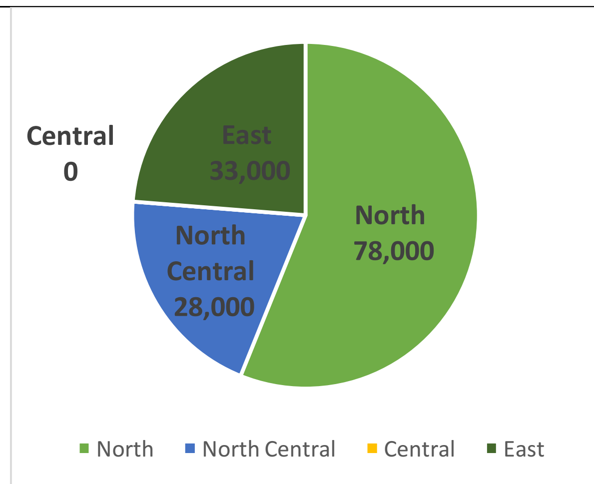
100% physical transaction costs
Allocation of acres



No transaction costs
Allocation of water



100% physical transaction costs
Allocation of water



	Water use per acre
North	1.0
North Central	1.6
Central	1.8
East	0.7
Total	**0.9**

	Water use per acre
North	1.0
North Central	1.2
Central	0
East	0.7
Total	**0.9**

Figure 10. Allocation of acres and water resulting from population growth, with and without physical transaction costs

What is driving the change in acres and water used in production? Producers use water in production up to the point where the marginal profit from water in production divided by acres equals the price of water received by the seller. As the price of water received by the seller (i.e., the price of water in their own region) changes, so does the total and relative amounts of water and acres used in production. Comparing no transaction costs to 100% physical transaction costs for East and North Central (the two regions with the largest change in acres), the per acre foot price of water received by the seller decreases in North Central from $19,000 to $16,000 and increases in East from $19,000 to $23,000 (Figure 11).

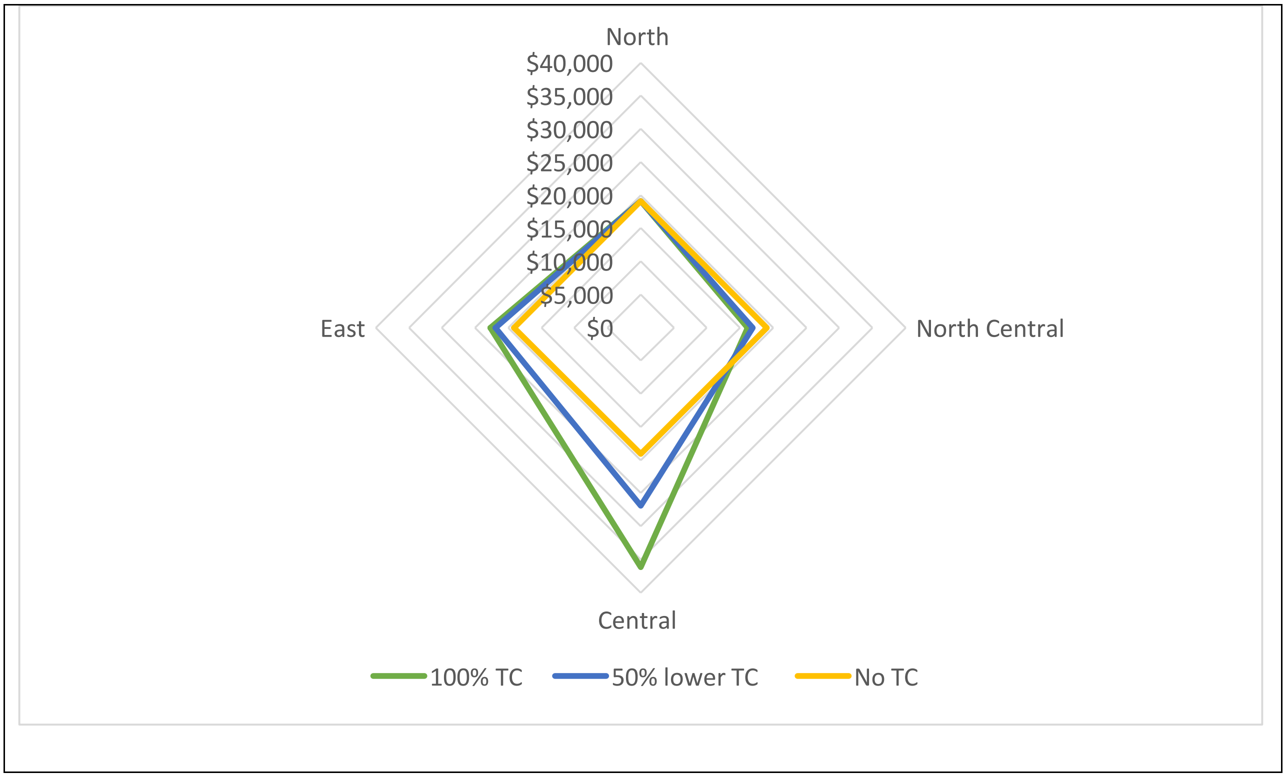


Figure 11. Price of water per acre foot received by seller as physical transaction costs decrease due to long run population growth

As water becomes less expensive in North Central, more water and more acres are used in production as the point at which the marginal profit from water in production divided by acres equals the price of water is higher. Additionally, as producers move to a new point on their production function, the most profitable mix of water and acres shifts to lower water use per acre. In East, on the other hand, as the price of water received by the seller increases, the amount of water and acres used in production decreases but the most profitable mix of water and acres remains the same.

When physical transaction costs are included in the water market model, the price of water received by the seller ranges from $16,000 to $36,000 per acre, given long run population growth and assuming full transaction costs. The price of water received by the seller in water scarce regions (Central) is much higher compared to the price of water received by the seller in water rich regions (North, North Central, and East). This is counter to the previous example with institutional transaction costs in which there was no regional heterogeneity in the price of water nor did the price of water change as transaction costs were decreased. Note that when physical transaction costs are zero, results are the same as in the previous example. The introduction of location specific transaction costs that vary based on the location of the buyer and seller illuminates the role that transaction costs play in a water market to create a price of water received by the seller that varies across regions and changes as transaction costs are lowered.

The municipalities in water scarce regions are forced to purchase water from outside of their region as the supply inside their region is not adequate to meet demand. Because they must purchase water from outside of their region, they incur physical transaction costs. Thus, the willingness to pay among municipalities' located in water scarce regions for an acre foot of water is the price of water in the region from which they are purchasing plus the physical transaction costs incurred. Given this is the municipalities' willingness to pay for water, producers in their own region are able to charge this same amount for water in their region; a higher price for their water than they would receive in the absence of transaction costs.

To illustrate, the Central region purchases water from its own region as well as from the North Central region. When purchasing from the North Central region, the municipality pays $16,000 plus physical transaction costs of $20,000 for a total of $36,000, which is equal to the price of water in the Central region. The story described here is the same dynamic as is described in the illustrative graphs in Figure 3 where North Central is Region 1 and Central is Region 2. As physical transaction costs decrease, the price of water remains relatively stable in water rich regions (with prices increasing or decreasing slightly depending on if water is purchased from an outside region) and decreases in water scarce regions. The impact of physical transaction costs on the price of water received by the seller is largely dependent on the heterogeneous nature of the water basin, where water scarce regions see a larger change in the price of water than do water rich regions.

While all producers benefit from population growth, given the presence of a water market and assuming physical transaction costs are present, the magnitude of the increase in profit depends on the regional price of water received by the seller (Figure 12). Producers in water scarce regions with high population growth see the largest benefit from transaction costs, Central's profits increase by $500 million when comparing no transaction costs to full physical transaction costs. In the water rich regions, profits remain the same with or without physical transaction costs except for North Central, which sees a $200 million decrease in profits comparing no transaction costs to full physical transaction costs. As physical transaction costs decrease, the impact on producer profits depends on where the producer is located. Those producers that gain the most from transaction costs (i.e., water scarce regions with large population growth), also lose the most as transaction costs decrease.

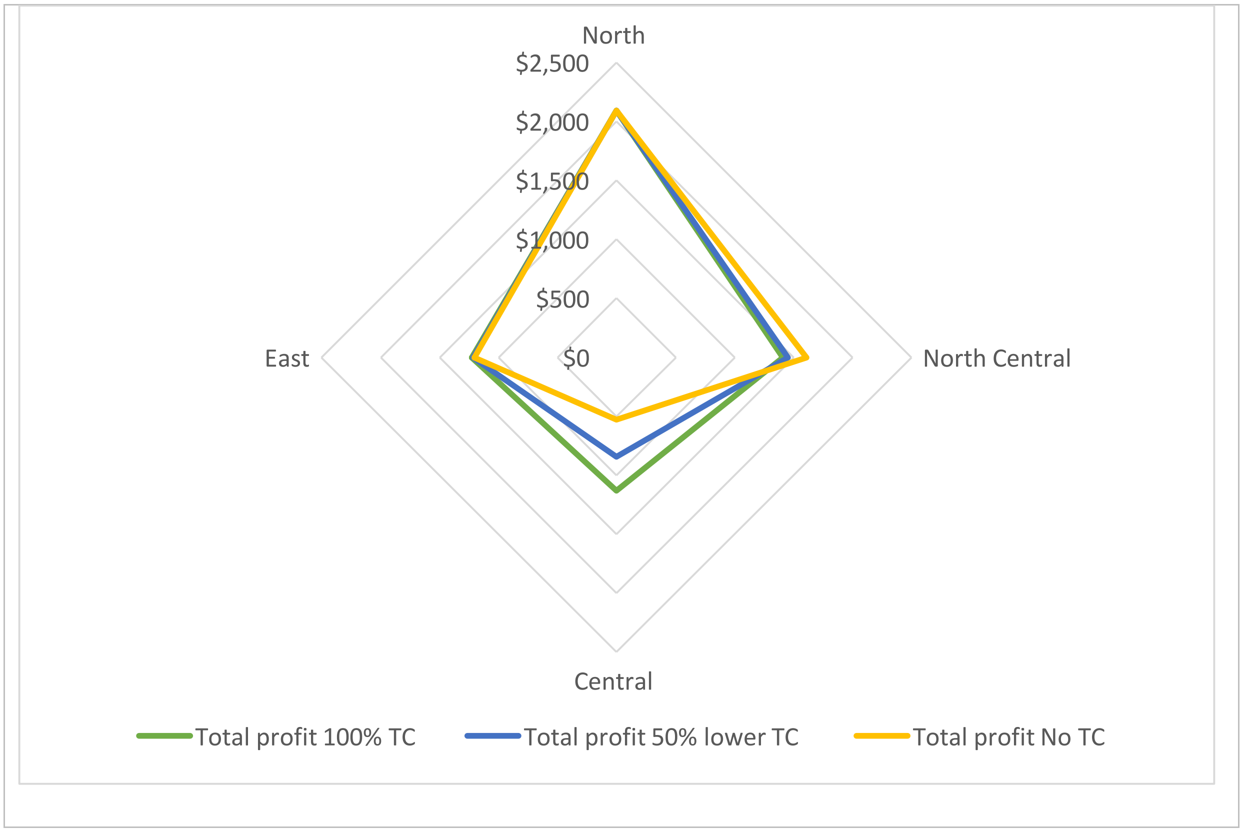


Figure 12. Producer profit as transaction costs are reduced (in millions)

The percent change in producer profits in the Central region resulting from population growth decreases from 140% to 27% as transaction costs are reduced from full physical transaction costs to a 100% reduction (Figure 13). Conversely, the North Central region sees profits from population growth increase from 3% to 18% as transaction costs are reduced from full physical transaction costs to a 100% reduction. Note that profits do not change until transaction costs are reduced by 40%. The change in profits for North and East is relatively stable as transaction costs are reduced.

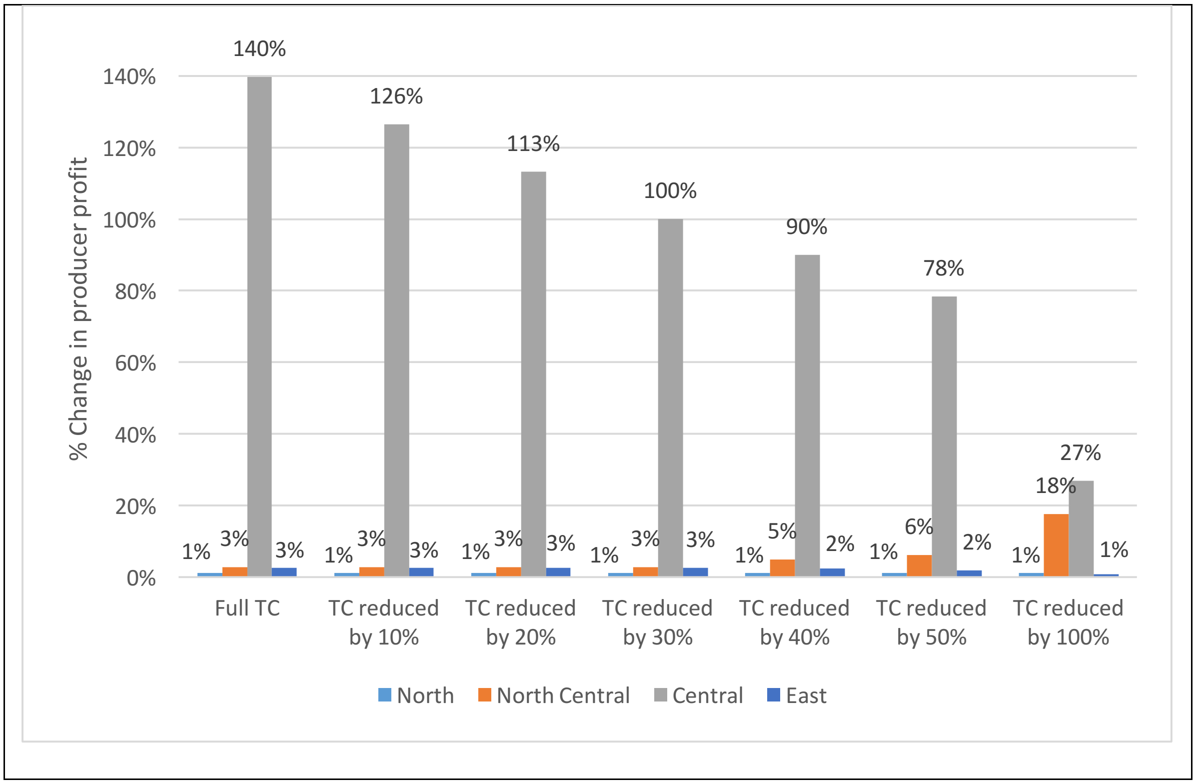


Figure 13. Percent change in producer profit comparing no population growth to long run population growth, as physical transaction costs decrease

Producers located in regions in water scarce regions with large population growth see a decrease in welfare associated with decreasing physical transaction costs. Producers located in water rich regions from which outside regions purchase water see an increase in welfare associated with decreasing physical transaction costs, albeit only at relatively large levels of a decrease in transaction costs. Results demonstrate that physical transaction costs do have an impact on producer profits in the face of population growth and, those impacts differ based on the location of the producer as a result of the regional heterogeneity in physical transaction costs.

For M&I firms, compared to the case with no transaction costs, physical transaction costs lead to an increase in the cost in water scarce regions to acquire water to meet future demand and a decrease in overall cost in water rich regions (Table 10). This difference demonstrates the dynamic impact of heterogeneous transaction costs, where the transaction cost itself is only part of the story, the market dynamics that create different regional prices also play a role in M&I costs to meet future demand for water. As transaction costs are reduced, all regions except for North Central see a decrease in the cost per capita to meet future demand. Compared to the case with institutional transaction costs, total costs incurred by municipalities are lower when only physical transaction costs are included.

Table 10. Cost per acre foot for M&I to acquire water as physical transaction costs decrease given population growth in 2050

Region	Full physical transaction costs	10% decrease	20% decrease	30% decrease	40% decrease	50% decrease	No transaction costs
North	$19,000	$19,000	$19,000	$19,000	$19,000	$19,000	$19,000
North Central	$16,00	$16,000	$16,000	$16,000	$17,00	$17,000	$19,000
Central	$36,000	$34,000	$32,000	$30,000	$29,000	$27,000	$19,000
South Metro	$43,000	$41,000	$39,000	$37,000	$35,000	$32,000	$19,000
East	$23,000	$23,000	$23,000	$23,000	$23,000	$22,000	$19,000
All regions	**$30,000**	**$29,000**	**$27,000**	**$26,000**	**$25,000**	**$24,000**	**$19,000**

The main driver of this difference is that all municipalities incur institutional transaction costs while only those that purchase water from an outside region incur physical transaction costs. As physical transaction costs decrease, the municipalities in water scarce regions (i.e. those who are incurring transaction costs) see a in reduction costs. Thus for customers in water scarce regions, a reduction of transaction costs will lead to a lower price for municipal water. For customers in water rich regions, there will be no change in price from a decrease in physical transaction costs.

2.4.4 Impacts of Institutional and Physical Transaction Costs

Characterizing transaction costs as including both the physical and institutional cost represents the most realistic specification of transaction costs. When both physical and institutional transaction costs are included in the water market model, acres and water used in production, the price of water received by the seller, and producer profits are the same as the case when only physical transaction costs are included; demonstrating that heterogeneous transaction costs (i.e., physical transaction costs) are the main driver behind price differentials across a basin. Because producers do not purchase water in the example presented in this paper, it is not the incursion of transaction costs that impacts producers.

Rather, physical transaction costs can shift the region from which water is purchased, affecting the price of water received by producers and thus acres and water used in production as well as profits. Because physical transaction costs differ across regions, they are the main driver behind where municipalities purchase water and how much they pay for that water, influencing the price of water in each region. Conversely, an increase in transaction costs that do not vary across regions (i.e. institutional transaction costs) will not impact where municipalities purchase water, and thus the price of water received by the seller.

While the regional price of water received by the seller is the same as the case when only physical transaction costs are included, the cost incurred by the buyer is not; the cost now includes both the institutional and physical component, thus increasing the total cost of acquiring water for all municipalities. Compared to the case with physical costs only, total cost incurred by municipalities to buy water is higher for all municipalities (12% to 31%) when both the physical and institutional component are included, ranging from $590 to $1,300 per capita depending on the region, assuming full transaction costs (Table 11).

Table 11. Cost per acre foot for M&I to acquire water as physical and institutional transaction costs decrease given population growth in 2050

Region	Full transaction costs	10% decrease	20% decrease	30% decrease	40% decrease	50% decrease	No transaction costs
North	$24,000	$24,000	$23,000	$23,000	$22,000	$22,000	$19,000
North Central	$21,000	$21,000	$20,000	$20,000	$20,000	$19,000	$20,000
Central	$41,000	$39,000	$36,000	$34,000	$32,000	$29,000	$19,000
South Metro	$48,000	$45,000	$43,000	$40,000	$38,000	$34,000	$19,000
East	$28,000	$27,000	$27,000	$26,000	$26,000	$24,000	$19,000
All regions	$35,000	$33,000	$31,000	$30,000	$28,000	$27,000	$19,000

As transaction costs decrease, all municipalities see a decrease in the cost to acquire water, in theory, leading to lower prices charged to household and industrial water users. As in the case with physical costs only, when both physical and institutional transaction costs decrease, the municipalities in water scarce regions (i.e. those who are incurring physical transaction costs) see a larger reduction in costs compared with water rich regions. Thus for customers in water scarce regions, a reduction of transaction costs will lead to a greater reduction in the price paid for municipal water compared to customers in water rich regions; although all customers will see some decrease in the cost of water as transaction costs are reduced.

2.4.5 Regional Economic Impacts

To evaluate how regional economies will change as a result of population growth and how transaction costs will change that impact, I estimate changes in revenue in one year with and without institutional and physical transaction costs and then use the estimated change in revenue to estimate regional economic impacts. Revenue from crop production is calculated simply as the revenue earned from one year of production. Revenue earned on the water market is calculated by taking the present value of the lump sum earned on the water market, assuming an interest rate of 3% and time period of 50 years, to determine the yearly proceeds generated from the water market.

Producers' that own water rights in the South Platte River Basin earn positive profits in the face of population growth because they are able to sell their water rights on the water market, but earn lower total revenues due to a decrease in the number of acres being farmed (Table 12). Without transaction costs, the basin-wide loss in revenue resulting from population growth is $39 million, and $53 million when full physical and institutional transaction costs are included, the revenue generated from the water market does not outweigh the loss in revenue generated from crop production. Total loss in revenue without transaction costs are estimated to be $164 million and increase to $169 million as full institutional and physical transaction costs are introduced. Profits earned on the water market without transaction costs are $125 million and decrease to $116 million with full physical and institutional transaction costs.

Table 12. Change in producer revenue for a single year due to long run population growth and physical and institutional transaction costs[12] (in millions)

Region	Full transaction costs	10% decrease	20% decrease	30% decrease	40% decrease	50% decrease	No transaction costs
Change in revenue from production							
North	$(37)	$(37)	$(37)	$(37)	$(37)	$(37)	$(36)
North Central	$(66)	$(66)	$(66)	$(66)	$(78)	$(82)	$(91)
Central	$(36)	$(36)	$(36)	$(36)	$(36)	$(36)	$(31)
East	$(30)	$(30)	$(30)	$(30)	$(12)	$(9)	$(6)
Total	**$(169)**	**$(169)**	**$(169)**	**$(169)**	**$(163)**	**$(164)**	**$(164)**
Change in revenue from sale of water							
North	$19	$19	$19	$19	$19	$19	$29
North Central	$35	$35	$35	$35	$42	$45	$60
Central	$44	$42	$39	$37	$35	$33	$23
East	$18	$18	$18	$18	$14	$13	$13
Total	**$116**	**$114**	**$111**	**$109**	**$110**	**$110**	**$125**
Total change in revenue							
North	$(18)	$(18)	$(18)	$(18)	$(18)	$(18)	$(7)
North Central	$(31)	$(31)	$(31)	$(31)	$(36)	$(37)	$(31)
Central	$8	$6	$3	$1	$(1)	$(3)	$(8)
East	$(12)	$(12)	$(12)	$(12)	$2	$4	$7
Total	**$(53)**	**$(55)**	**$(58)**	**$(60)**	**$(53)**	**$(54)**	**$(39)**

This decrease in revenue is likely to have a negative impact on those in the agricultural communities that support farmers. As revenue earned by producers for production decreases, those who supply inputs and support services will see a decrease in revenue in their own businesses, creating a decrease in local economic activity for agricultural communities. While some of the revenue generated from the sale of water rights will be spent in the local community, it is likely that a portion of that revenue will leave the local community as the number of acres remaining in farming decreases.

[12] This assumes revenue generated from one year of crop production and from the annualized revenue generated from the sale of a water right (assuming a 3% interest rate and 50 year time horizon).

Looking at the total change in revenue as transaction costs decrease highlights some of the market dynamics that occur as a result of heterogeneous transaction costs. Once transaction costs decrease by 40%, a switching occurs and producers enter the water market. Whereas at higher transaction costs, only municipalities purchased water. This changes the amount of water purchased by different regions and thus impacts revenues.

Next, I expand on the direct economic impact of population growth that results from a decrease in producer revenue and evaluate what that impact means for the economy in each of the regions. I use the commonly employed input-output model: specifically, the commercially available software IMPLAN (IMpact Analysis for PLANning) from the IMPLAN Group LLC (Minnesota IMPLAN Group, Inc., 2000), to calculate the total economic impact of population growth for the South Platte River Basin[13].

Results are calculated with and without transaction costs for three different scenarios. The first scenario assumes all money earned from the sale of water rights leaves the region, producers sell their water and leave the region. The second scenario assumes producers remain in the region and spend half of the annual value of proceeds earned from the sale of water rights in their region. The last scenario assumes producers remain in the region and spend the full value of the annual proceeds from the sale of water rights within their region. Scenarios are based off previous research that has found that the impact of a water market on the health of rural economies is largely dependent on whether those who sell their water choose to remain in the region or choose to leave (Bourgeon, Easter, and Smith, 2008).

[13] Note that acres are allocated to each region based on where the water is diverted, which may or may not be the same region in which the acres are located. The regions created in IMPLAN assume the region where water is diverted is the same region where it is used, potentially leading to a small over-estimation of impacts in some regions and underestimation in others. Due to its upstream location, water is diverted in North but used in North Central or other downstream regions. Irrigated acres located in North are higher than in reality, whereas irrigated acres in North Central are lower.

The impact of change in revenue[14] resulting from a change in production is modeled as a decrease in revenue for the agricultural sector[15] and changes in revenue resulting from the sale of water rights are modeled as an increase in household revenue for the median income households in each region[16]. Based on this modeling choice, the economic impact for the agricultural sector remains the same throughout all scenarios as only the portion of money included as household revenue changes with each of the three scenarios.

The direct impact represents the change in revenue from production and the sale of water rights. The indirect impact represents the change in sales, income and jobs in the sectors that supply goods to the agricultural industry and to households (e.g., a decrease in revenue from production decreases purchases from agricultural input suppliers). And, the induced impact results from the employees of the agricultural sector purchasing goods and services at a household level.

The total direct economic impact for the South Platte River Basin for one year resulting from long run population growth ranges from negative \$53 million to negative \$169 million, depending on how much money earned on the water market is assumed to be spent locally and increases to a range of negative \$204 million to negative \$343 million when all impacts are considered (Table 13). The North Central region sees the largest negative impacts, with total impacts ranging from negative \$89 million to negative \$106 million.

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[14] Change in revenue is used as a proxy for a change in final demand. Although this approach is commonly utilized, it leads to an overestimation of impacts due to double counting.
[15] NAICS sector 11 (Agriculture, Forestry, Fishing and Hunting), with forestry, fishing and hunting removed
[16] Median household income calculated from the American Community Survey (https://www.census.gov/programs-surveys/acs)

Table 13. Economic impact in a single year resulting from long run population growth and full physical and institutional transaction costs (in millions)

Region	Direct Impact			Total Impact for all Industries (Direct + Indirect + Induced)		
	Water sellers leave region	Assume half of proceeds from water market spent locally	Assume all of proceeds from water market spent locally	Water sellers leave region	Assume half of proceeds from water market spent locally	Assume all of proceeds from water market spent locally
North	($37)	($27)	($17)	($55)	($46)	($37)
North Central	($66)	($49)	($31)	($106)	($97)	($89)
Central	($36)	($14)	$8	($63)	($38)	($13)
East	($30)	($21)	($12)	($50)	($45)	($40)
Total	**($169)**	**($111)**	**($53)**	**($343)**	**($274)**	**($204)**

What do these economic impacts mean relative to economic activity in the agricultural industry as well as the economy as a whole? The two regions with the largest agricultural output are North Central and East, with the agricultural industry accounting for 88% and 22% of total regional output, respectively (Table 14). The total economic impact in one year for the agricultural sector as a result of long run population growth in the North Central region is negative $87 million and negative $40 million for the East region, representing 1% and 3% of regional agricultural output, respectively. Give the relative importance of agriculture in those communities, the change in revenue resulting from population growth will impact many households and businesses in the regions.

Table 14. Economic impacts resulting from long run population growth and full physical and institutional transaction costs relative to the size of the agricultural sector and overall economy (in millions)

	Total Impact for the Agricultural Sector	Total Output of the Agricultural Sector	Total Output in the region	% Change in the Agricultural Sector	Portion of Total Output Attributed to the Agricultural Sector
North	($38)	$324	$71,967	-12%	0.5%
North Central	($87)	$16,778	$19,084	-1%	88%
Central	($37)	$246	$244,553	-15%	0.1%
East	($40)	$1,410	$6,314	-3%	22%
Total	**($213)**	**$3,855**	**$362,079**	**-6%**	**1%**

Total impacts for the agricultural sector in the South Platte River Basin are a negative $213 million, representing 6% of total agricultural output. While individual producers who own water rights see an increase in profit resulting from long run population growth, the local economy where they are located has a decrease in economic activity, particularly within the agricultural sector. For rural communities that rely on agriculture, long run population growth will have a negative impact as producers sell their water and land is taken out of production since the operating activities and production expenses associated with that land will cease.

2.5 Conclusion: Transaction Costs

This chapter contributes twofold to the analysis of resource markets with a specific focus on water markets. First, I present an optimization modeling approach with multiple, integrated, regional water markets consisting of heterogeneous firms, both in terms of objectives and situation. Producers are assumed to maximize expected profit; whereas the goal of M&I firms is to minimize the cost of acquiring enough water rights to meet forecasted demand. This framework allows for each individual to optimize their own objective function, for different types of firms to have different objective functions, and lastly, allows for the inclusion of heterogeneous transaction costs.

Although the example described in this paper focuses on a water market, this same framework could be expanded to other resource markets for which the good and firms are heterogeneous and transaction costs exist (e.g., land). Second, I utilize a model calibrated with data from a Colorado river basin to demonstrate the impact of transaction costs on how much and where water shifts out of agricultural production, producer profits and revenues, and municipal costs in the presence of population growth.

Results from this paper demonstrate that heterogeneous firms and the existence of both physical and institutional transaction costs play a role in welfare outcomes from the water market, showing the importance of including heterogeneous transaction costs in a model of a water market to provide policy and market analysis. To evaluate how the presence of transaction costs in water markets impacts welfare outcomes, both in terms of overall efficiency and distributional impacts, results focus on three aspects: (1) how much water is sold from producers to M&I firms and where those trades take place, (2) producer profits/revenues, (2) and M&I costs. These results are evaluated for five scenarios, the first scenario evaluates the impact of population growth under current institutional settings, serving as the base case. The remaining scenarios evaluate how transaction costs in a water market impact welfare outcomes. Scenarios include: impacts of population growth, impacts of institutional transaction costs, impacts of physical transaction costs, impacts of both types of transaction costs, and lastly regional economic impacts of population growth with and without transaction costs.

Results from this model predict that irrigated acres used in production for the South Platte River Basin will decrease from 290,000 acres to 150,000 acres as a result of population growth, given current institutional settings. As to be expected, water rich regions that are conveniently located adjacent to water scarce regions with population growth see the largest decrease in irrigated acres. Comparing producer profit with zero population growth to profits with long run population growth and current institutional settings, total producer profit across all regions increases with long run population growth by 15%; the present value of a future stream of profits earned from production decrease, but profits earned from selling water increase. In total, slightly over half of all producer profits result from the sale of water rights. Producer profits increase slightly (1%) in water rich regions, while producers located in water scarce regions with high population growth see the largest increase in profit (27%). Producers that own water rights earn positive profits in the face of population growth because they are able to sell their water rights on the water market, but earn lower total revenues due to a decrease in the number of acres being farmed.

In the case of institutional transaction costs, as a result of the assumption of homogeneity of the transaction cost, the allocation of acres across regions resulting from population growth comparing no transaction costs and 100% institutional transaction costs is virtually unchanged. Although institutional transaction costs increase the cost of purchasing water, they do not change the relative cost of purchasing water across regions. Thus, given the inelastic nature of M&I demand, the inclusion of homogeneous transaction costs do not change the allocation of acres in the face of population growth compared to the case without transaction costs.

Similarly, producer profits do not change as institutional transaction costs decrease. Producer profits do not change as institutional transaction costs decrease because the price of water received by the seller does not change. Institutional transaction costs are assumed to be homogeneous across regions and are incurred regardless of the location of the water buyer and seller, resulting in a price of water received by the seller that does not vary across regions, regardless of the size of the transaction costs.

M&I costs, on the other hand, are impacted by institutional transaction costs. Compared to the case with full institutional transaction costs, for each 10% reduction in institutional transaction costs, the cost for M&I to acquire water decreases by 2% for all regions. Municipalities, and therefore their customers, benefit from a reduction in institutional transaction costs. When governments have discussed decreasing transaction costs (e.g., Iseman et al., 2012), the discussion is typically centered on making it easier to transfer water between users from a legal standpoint. An interesting result from this research is that reducing transaction costs that do not vary across regions is likely to have a minimal impact on the functioning of a water market and the associated producer welfare outcomes until the price of water rights becomes high enough to deter development.

The introduction of location specific transaction costs illuminates the role that transaction costs play in a water market. Physical transaction costs, assumed to vary by region, do not change the total amount of water purchased by M&I (given the characterization of M&I demand as perfectly inelastic), but they do shift from which region water is purchased as well as the most profitable mix of acres and water chosen by the producer. Some regions have the same number of acres in production while others have either more or fewer acres in production. This shift in acres is as a result of a price of water received by the seller that varies across regions and changes as physical transaction costs are reduced.

The price of water received by the seller in water scarce regions is much higher compared to the price of water received by the seller in water rich regions. This is counter to the case with homogeneous transaction costs, in which the price of water did not vary across regions. As physical transaction costs decrease, the impact on producer profits depends on where the producer is located. Those producers that gain the most from transaction costs (i.e., water scarce regions with large population growth), also lose the most as transaction costs decrease. As physical transaction costs decrease, the municipalities in water scarce regions (i.e. those who are incurring transaction costs) see a reduction in costs. Thus, for customers in water scarce regions, a reduction of transaction costs will lead to a lower price for municipal water. For customers in water rich regions, there will be no change in price from a decrease in physical transaction costs.

When both physical and institutional transaction costs are included, all results, with the exception of M&I costs are the same as the case when only physical transaction costs are included, demonstrating that the heterogeneous costs associated with transferring water are the main driver behind price differentials across a basin. Compared to the case with physical costs only, total cost incurred by municipalities to buy water is higher for all municipalities (12% to 31%) when both the physical and institutional component are included. As transaction costs decrease, all municipalities see a decrease in the cost to acquire water. For customers in water scarce regions, a reduction of transaction costs will lead to a greater reduction in the price paid for municipal water compared to customers in water rich regions; although all customers will see some decrease in the cost of water as transaction costs are reduced.

Results from the model presented in this chapter demonstrate the importance of including heterogeneous transaction costs into a water market model as these costs have a large impact on the welfare outcomes associated with water markets, both in terms of overall efficiency and distributional impacts. Overall, producers that own water rights benefit from population growth given the existence of a water market, but those gains vary greatly across users based on their location within the basin. This difference is driven by transaction costs, and largely by the physical transaction costs that vary based on location.

Limitations of this model include the following. The model overestimates the amount of water that will be purchased on the water market by not including the choice of conservation and new supply, both of which will be utilized by municipalities in the South Platte River Basin to meet future demand for water (addressed in the following chapter). The effects of climate change on water supply are not considered in this model. Given the static nature of this model, the dynamic impacts that occur based on a decision in one time period influencing the next are not considered.

Chapter 3: Estimating the Impact of Conservation and New Supply on Welfare in the Presence of a Water Market with Heterogeneous Transaction costs

Increased demand for urban water, fueled by population growth in the water constrained regions of the western U.S., is projected to lead to a gap between existing water supply and future demands for water. Through the 1970's, water supply management consisted of increasing water supply through building infrastructure such as dams, reservoirs and canals, but since that time, due to the high cost of new supply development, the focus has shifted to policies aimed at more effective management and reallocation of existing supplies (Chong and Sunding, 2006). The gap between existing water supplies and future demand for water will likely be met through a "portfolio" approach, where utilities use a combination of new infrastructure, water transfers, and conservation to close the gap. (SWSI, 2011).

Market based, voluntary transfers of water have long been promoted by economists based on the idea that, under perfectly competitive market conditions, they lead to an efficient allocation of water (Booker, et al., 2012; Booker and Young, 1994). Empirical studies of water markets in the West have shown there are potential economic gains from reallocating water through water markets (Brewer, et al., 2007; Colby, Crandall, and Bush, 1993; Howe and Goemans, 2003). But increasingly, utilities are looking at conservation as an alternative, demand side measure, to balance the supply and demand gap created by population growth (SWSI, 2011). Conservation is an appealing alternative to supply side measures due to the high cost of building new infrastructure (Booker et al., 2012) and the concern that water transfers from agriculture to municipalities lead to a decrease in economic activity for rural communities (Bourgeon, Easter, and Smith, 2008). The objective of this paper is to estimate the impact of utilizing a portfolio approach to meeting future M&I demand for water. Specifically, I estimate the impact of conservation and new supply development on regional economies in the presence of a water market, including impacts to both agricultural and urban water users.

Achieving water savings through conservation has been identified as a readily available, and potentially low-cost, means by which to meet increasing demand (Ahmad and Prashar, 2010; Rosenberg, Howitt and Lund, 2008) and is an important strategy currently employed in many western states. For example, "In order to meet Colorado's water management objectives, a mix of local water projects and processes, conservation, reuse, agricultural transfers, and the development of new water supplies should be pursued concurrently (SWSI, 2011, p.2)." Yet little is known about the welfare impacts of conservation and new supply development on water rights holders.

Dynamic optimization models have been utilized to analyze a portfolio approach to meet future demand for water. These studies found that the least cost means by which to meet future demand will include a combination of building new supply, water transfers, and municipal conservation (Ahmad and Prashar, 2010; Gillig, McCarl, and Boadu, 2001; Jenkins and Lund, 2000; Zhu, Marques, and Lund, 2015). Although conservation and new supply were identified as important parts of the portfolio of options to meet future demand for water, previous research has not evaluated the impact of these measures on the well-being of the water users in the river basin (i.e., who wins and who loses as a result of these measures); rather, the least cost means by which future demand will be met was identified.

Gillig, McCarl, and Boadu (2001) and Rosenberg, Howitt and Lund (2008) use a stochastic nonlinear programming modeling approach and find that urban water conservation leads to an increase in total regional welfare, due to the lower cost of conservation compared to alternative water sources. These studies found an increase in welfare across all users in a river basin resulting from conservation, but did not evaluate the impact of conservation across individual water users. While there is evidence from the literature that conservation can lead to an increase in overall regional welfare, it is unclear how conservation impacts producers and how a producer's location within a basin might influence those impacts. Conservation has been promoted, in part, to help agricultural and rural communities, but how producers will be impacted by conservation is largely unknown.

Compared to conservation, new supply development is typically very expensive, has a long planning horizon and is often very contentious, due to potentially negative environmental impacts. For example, the planning process for Northern Integrated Supply Project (NISP), a new supply project in northern Colorado that will provide water to North and North Central, began in 2004 and remains in the planning process in 2016; $17 million has been spent on the planning process thus far and current estimates of the entire project are $700 million (Duggan, 2016). While the model presented in this paper is not able to evaluate the environmental impacts of new supply development, it is able to evaluate the economic outcomes for municipalities and rural economies that result from new supply development, an important piece of the discussion.

Building from previous literature I examine how conservation and infrastructure projects impact water market activity and the resulting welfare impacts (this may or may not be the least cost solution). In a least cost analysis, perfectly competitive market conditions are assumed (or implied); thus if the market is characterized by perfectly competitive market conditions results will be the same, but if not results will differ. I expand on Zhu, Marques, and Lund (2015) to include heterogeneity across water user type, location, and transaction costs as well as to evaluate the welfare impacts of pursuing both conservation and new supply initiatives.

This paper will address the following research questions: One, what is the impact of introducing conservation and new supply into a water market on the costs to meet future demand for water? Two, what impact does introducing conservation and new supply into a water market have on the welfare of agricultural producers and the economic activity of rural communities?

Conservation has been promoted as a least cost-means of meeting future demands while simultaneously decreasing the pressure to reallocate water from agriculture to municipalities and, in theory, minimize the impact on rural communities (e.g., Ahmad and Prashar, 2010; Jenkins and Lund, 2000; SWSI, 2010). This research will estimate the potential cost savings resulting from conservation as well as estimate the impact of conservation on producer welfare and the economic impacts on rural communities. Contrary to previous studies, this research will provide researchers and policy makers with the welfare outcomes associated with commonly discussed means by which future demand for water will be met, providing insight into the winners and losers associated with differing policy prescriptions. Specifically, this paper will evaluate the impact of conservation and new supply in the presence of a water market on the cost for municipalities to acquire water in order to meet future demand, market activity, and the profitability and total revenue generated by agriculture.

The remainder of the paper is organized as follows. The next section will provide background and literature review on utilizing a portfolio approach to meet future demand for water. This is followed by the water rights allocation section that describes the methodological framework for the model developed in this paper, including a discussion of the producer problem, the municipal problem, and the impact of conservation and new supply on market equilibrium. Next, the data section presents the data used in the simulation portion of the study.

The results section describes the impact of conservation and new supply on municipal cost, producer profit, and regional economic impacts. The paper ends with concluding remarks.

3.1 Background: A Portfolio Approach to Meeting Future Demand for Water

The literature has traditionally focused on supply side measures, namely water markets, as the means by which future demand for water will be met. Water markets are commonly modeled using optimization techniques and have been used extensively to examine water markets (Harou, et al., 2009 survey many approaches, current examples include Jiang and Grafton, 2012 and Howitt, et al., 2012). Results from these models demonstrate that water markets can lead to an increase in basin-wide welfare (or mitigation of welfare losses) by allowing water to move from lower valued uses (i.e., agriculture) to higher valued uses (i.e., municipalities). Empirical models of water markets have found that the key factors influencing the price and quantity of water transferred: (a) whether or not the transaction involves a change in use or location, (b) the relative reliability of the water right (i.e., seniority), and (c) the presence of physical and/or institutional transaction costs (Colby, Crandall & Bush, 1994; Pullen & Colby, 2008; Payne, Smith & Landry, 2014).

While conservation and new supply are not commonly included, they have been included in some water market models. Gillig, McCarl, and Boadu (2001) construct a stochastic mathematical programming model to evaluate the impact of proposed plans for meeting 2050 water demand. Plans include building new supply, water transfers, and conservation. They find that due to the high cost of building new supply and demand elasticity response to higher prices, in addition to water transfers and building new supply, efficiency dictates that a portion of water needs will be met due to water savings from price-induced conservation. They find a slight increase in overall welfare, but neither the specific welfare impacts nor distributional impacts of conservation are evaluated.

Rosenberg, Howitt and Lund (2008) use a stochastic nonlinear programming to determine the optimal allocation of conservation (for agriculture and municipalities), leak reduction, and supply expansion as the means by which to meet increased demand for water resulting from population growth. They find that urban water conservation generates substantial regional economic benefits and can delay the need to invest in infrastructure expansion.

Supply side measures, such as water markets, have raised significant concerns over the impacts of water transfers out of agriculture on the agricultural producers and rural communities (Booker, Howitt, Michelsen, & Young, 2012; Bourgeon, Easter, and Smith, 2008). Conservation has been promoted as a means by which to meet future demands that decreases transfers of water from agriculture to municipalities and, in theory, minimize the impact on rural communities (e.g., Ahmad and Prashar, 2010; Jenkins and Lund, 2000; SWSI, 2010). The focus of the literature on water markets in which conservation is included has been least cost scenario analysis rather than a welfare analysis.

Wilchfort and Lund (1997) use a two-stage linear programming model and find that when there are limitations placed on water transfers (both spot market and permanent) due to drought conditions, it encourages long term municipal conservation measures. Watkins and McKinney (1999) develop a two stage modeling approach that incorporates building new supply, purchasing water, and municipal conservation as a means by which to meet projected shortfalls due to population growth. Results show that if one assumes current climatic conditions will continue, demand side management (i.e., water conservation, reuse, spot market transfers) will provide adequate water for the basin used in the study. But, under severe drought conditions, either large investments in infrastructure or a substantial reduction in projected water use will be required to meet future water demand.

Jenkins and Lund (2000) incorporate municipal conservation into a combined water supply yield simulation and least-cost shortage management model and find that, in addition to short term water transfers, both short- and long-term conservation will be used to manage the risk of municipal water shortfall. Ahmad and Prashar (2010) use a system dynamics modeling approach and find that water conservation in the municipal sector is an effective strategy to alleviate some of the competition for scarce water resources due to population growth. Zhu, Marques, and Lund (2015) incorporate urban water conservation into a single objective function in a two-stage stochastic programming approach to model regional water allocation between agriculture and urban water users. They find that water transfers provide incentives for coordinating urban and agricultural water conservation to better match the likelihood of water availability.

Because the focus of the previous literature has been on the potential efficiency gains from conservation, there remains little understanding of the impacts of conservation and new supply on producers and rural communities. Why do the impacts of conservation to the agricultural community matter? For producers that own water rights and plan to remain in agriculture, while they do not want to sell their water rights, they can use the value of their water as collateral to borrow money[17]. For producers that own water rights and plan to use their water rights to retire, the asset value of their water is of primary importance as it represents a significant portion of many farmer's retirement portfolios. And for the general members of agricultural community, the asset value of the water in their community will impact the potential

[17] A producer can use the value of their water rights on the open market as collateral for a loan, but the ability to do so is subject to the creditor's ability to determine the transferability of the water right and its value.

regional revenue generated by community members. Conservation and new supply development will have an impact on the price of a water right and the quantity of water transferred out of agriculture, and thus the welfare of the agricultural community. These impacts are likely to be heterogeneous depending on the region in which producers are located.

When conservation and new supply are included in a least cost scenario analysis, perfectly competitive market conditions are assumed (or implied) and the water market is not explicitly modeled. Contrary to previous optimization modeling approaches, I model multiple, integrated, regional water markets consisting of heterogeneous firms, both in terms of objectives and situation. Producers are assumed to maximize expected profit; whereas the goal of municipal firms is to minimize the cost to meet forecasted demand by choosing to purchase water rights, conservation and/or new supply. Transaction costs are incurred by buyers. In reality, the municipality does not directly purchase water for new development, but rather generally require developers to purchase the right to use a specific quantity of water or cash in lieu for each new water tap before they are given the permit to build (e.g., City of Loveland, 2016). Traditionally, municipalities require developers to secure enough water to maintain system reliability given the additional demand associated with the new tap, often called firm yield (Griffin & Mjelde, 2000).

My approach is consistent with Zhu, Marques, and Lund (2015), in which future municipal demand for water does not change as the price of water changes. This is contrary to many previous hydro-economic models with both producer and municipal firms, in which municipal firms maximize a net benefit function derived from consumer demand for water (e.g., Rosegrant, et al., 2000; Babel, Gupta, & Nayak, 2005). The approach utilized in this paper more accurately represents the fact that municipalities require developers to purchase water rights that produce a particular level of firm yield so as to minimize the risk of a shortage rather than based on the prices their customers are willing to pay for water.

The multi-objective framework adopted here builds off the model developed in Chapter 2 by allowing municipalities to purchase conservation and new supply in addition to purchasing water on the water market. Unlike previous water market models that evaluate conservation and new supply, this model includes heterogeneous transaction costs associated with buying water[18]. It has been well documented that transaction costs exist in water rights markets and have a heterogeneous impact on the price of water (e.g., Colby, 1990; Brookshire, Colby, Ewers & Granderton, 2004; Payne, Smith & Landry, 2014), thus including heterogeneous transaction costs in a water market model allows for a more accurate characterization of welfare outcomes.

3.2 Water Rights Allocation Model with Conservation and New Supply

The water rights allocation model described in this paper builds directly from the model presented in Chapter 2 by allowing municipalities to meet future demand by not only purchasing water rights, but also by investing in conservation and new supply. As before, assume there are i firms in a river basin consisting of producer and M&I firms, in which each is a subset of the i firms that make up the basin. Producers maximize profit by using water in production, buying water and selling water. M&I firms minimize the cost of securing a water supply capable of meeting future demands through a combination of water rights purchases, investment in conservation, and the development of new supply projects. Water right prices are endogenously determined as a function of the supply and demand for water in each region. The producer problem, the M&I problem, as well as the characterization and impact of conservation and new supply on the market equilibrium and resulting producer welfare will be discussed in greater detail in the remainder of this section.

[18] Zhu, Marques, and Lund (2015) include a constant transaction cost associated with water transfers.

Figure 14 describes the conceptual framework for the model, showing an example of a water market with two regions - one in which water is plentiful (Region 1) and one in which water is scarce (Region 2) - and two types of firms (municipal and agricultural). The water rights held by agricultural producers in Region 2 are not sufficient to meet municipal demand, so, in addition to purchasing water rights from producers in their own region, municipalities in Region 2 purchase water from Regional Pool 1.[19] Each user faces transaction costs associated with buying water from other users depending on their relative locations, effectively creating different "pools" of water. When purchasing water from one's own regional pool, a firm faces institutional transaction costs only. When purchasing water from an outside regional pool, a firm faces both institutional and physical transaction costs. The amount of water bought from and sold to each regional pool determines the price of water in each regional pool.

[19] In this model, all water bought and sold is in terms of the consumptively used portion of the water, where consumptive use is defined as a water use that permanently removes water from its source. This is based on water law throughout the western U.S. in which only the consumptively used portion of a water right can be sold so as to not harm other water users in the river basin (Hobbs Jr., 2004). Producers sell the consumptively used portion of a water right and municipalities purchase the consumptive use portion of their future demand.

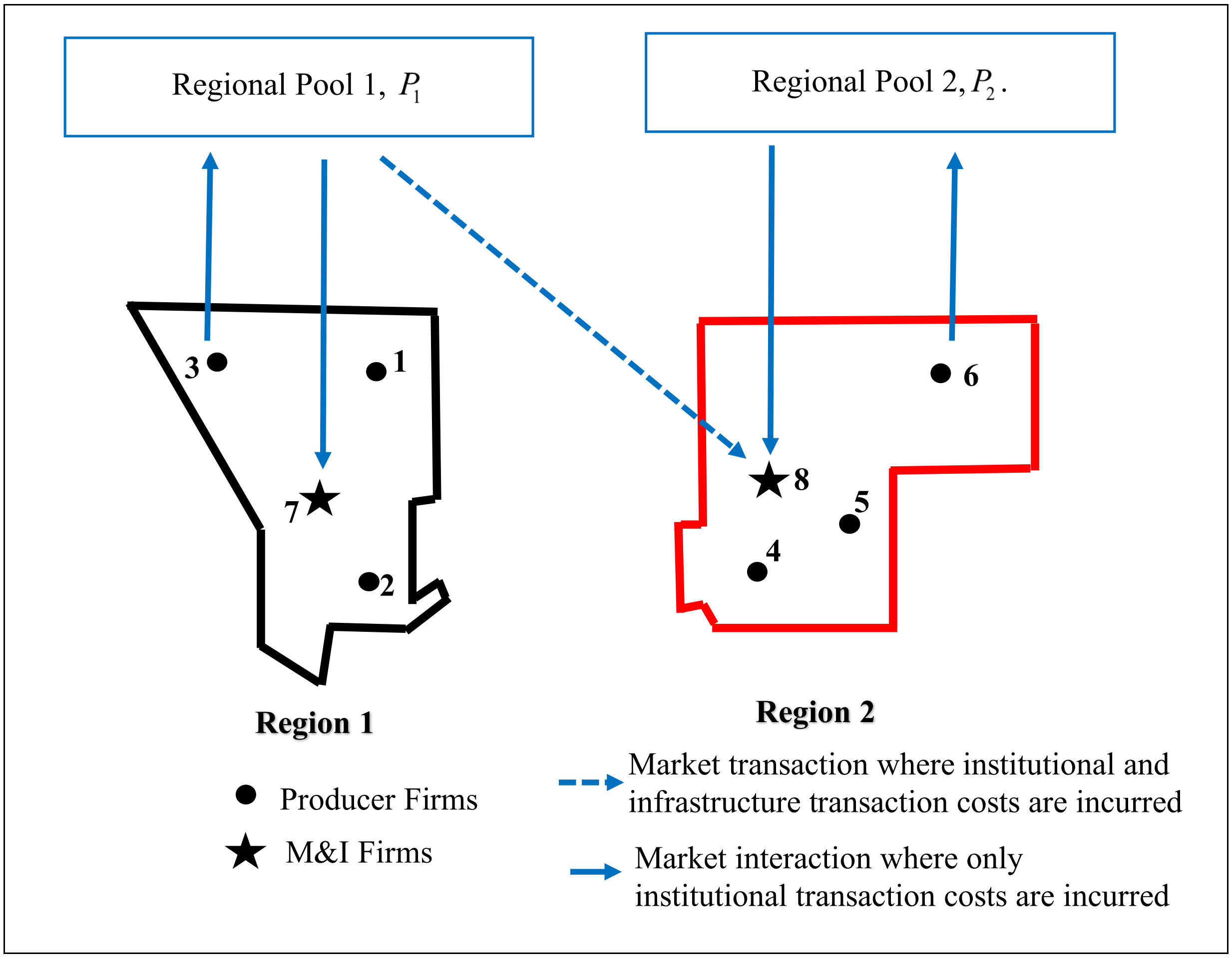

Figure 14. Conceptual framework of market interaction between buyers and sellers when transaction costs are present.

Institutional transaction costs are the legal component and are assumed to remain constant across regions. Physical transaction costs are the infrastructure costs associated with purchasing water, varying across users based on location. These costs are very low for purchasing within a region and increase significantly when purchasing from an outside region; mimicking the idea that a buyer is located conveniently to some regions but not others given existing water delivery systems. When multiple regions are introduced, the existence of transaction costs drives regional differences in the quantity of water purchased from each region as well as the regional price of water. The following sub-sections outline the producer and M&I problems, as well as the market setting in more detail.

3.2.1 Producer Problem

Producers maximize profit by choosing the amount of water and acres to use in production as well as the amount of water to buy or sell on the water market, which consists of multiple regional pools. Municipal conservation does not change the producer problem, rather indirectly impacts the producer's optimal use of water via its effect on the market price of water. The producer profit maximization problem is as follows[20]:

$$
\begin{aligned}
\max_{w,A,s,b} \quad & \pi_i = P_{y,i}F_i(w_i, A_i) - c_{w,i}A_i w_i - c_{A,i}A_i + \sum_r \left(P_{w,r}s_{i,r} - P_{w,r}b_{i,r} - tc_{i,r}(b_{i,r}) \right) \\
s.t. \quad & \\
& w_i \geq 0 \\
& A_i \geq 0 \\
& s_{i,r} \geq 0 \\
& b_{i,r} \geq 0 \\
& w_i A_i + \sum_r s_{i,r} \leq \overline{W}_i + \sum_r b_{i,r} \\
& A_i \leq \overline{A}_i
\end{aligned}
\tag{13}
$$

where $P_{y,i}$ is the output price per unit for producer *i*. Each of the *i* producers differ in the crop they produce and/or the region in which they are located and has a unique production function. $F_i(\cdot)$ is the production function for producer *i* describing output where w_i is water use per acre by firm *i*, A_i acres used in production by producer *i*, $c_{w,i}$ is the cost per unit of using water in production for producer *i*, and $c_{A,i}$ is the cost of production per acre for producer *i*.

$P_{w,r}$ equals the price per unit of water bought/sold from regional pool *r*, $s_{i,r}$ is the amount of water sold by producer *i* into regional pool *r*, and $b_{i,r}$ is the amount of water bought by producer *i* from regional pool *r*, and $tc_{i,r}(b_{i,r})$ is the transaction cost as a function of the volume

[20] Based on Colorado water law, producers can only sell the consumptive use portion of their water right, defined as a water use that permanently removes water from its source (Hobbs Jr., 2004). Therefore, only the consumptively used portion of a producer's water right is included in this model.

of water bought that is incurred by firm *i* from transferring water from regional pool *r*. Transaction costs, $tc_{i,r}$, consist of two types of transaction costs, institutional and physical where $tc_{i,r} = tcI_{i,r} + tcP_{i,r}$. I assume the technology set for each producer is convex, monotonic, closed, bounded, and non-empty (e.g., $F_i^{'}(\cdot) \geq 0, F_i^{''}(\cdot) \leq 0 \ \forall_i$). Each producer is endowed the consumptive use portion of their current endowment of water, $\bar{W}_i$, calculated as a percentage of average diversions and $\bar{A}_i$ is initial endowment of acres for producer *i*.

The resulting Lagrangian is as follows:

$$L_i = P_{y,i}F_i(w_i, A_i) - c_{w,i}A_i w_i - c_{A,i}A_i + \sum_r \left(P_{w,r}s_{i,r} - P_{w,r}b_{i,r} - tc_{i,r}(b_{i,r})\right) + \lambda_i\left(\bar{W}_i + \sum_r b_{i,r} - w_i A_i + \sum_r s_{i,r}\right) + \delta_i(\bar{A}_i - A_i) \quad (14)$$

where λ_i is the value of relaxing the constraint on water available to the producer by one unit and δ_i is the value of relaxing the constraint on land use by one unit. Both represent the producer's willingness to pay for an additional unit of water and land, respectively. The solutions to this problem are $w_i, A_i, s_{i,r}, b_{i,r}, \lambda_i$, and δ_i and satisfy the following first order conditions:

$$
\begin{aligned}
&\frac{\partial L_i}{\partial w_i} = P_y F_w(w_i, A_i) - c_{w,i} A_i - A_i \lambda_i \leq 0 && \text{c.s. } w_i \geq 0 \\
&\frac{\partial L_i}{\partial A_i} = P_y F_A(w_i, A_i) - c_{w,i} w_i - c_{A,i} - \lambda_i w_i - \delta_i \leq 0 && \text{c.s. A}_i \geq 0 \\
&\frac{\partial L_i}{\partial s_{i,r}} = P_w - \lambda_i \leq 0 && \text{c.s. s}_{i,r} \geq 0 \\
&\frac{\partial L_i}{\partial b_{i.,r}} = -P_w - tc(b_{i,r}) + \lambda_i \leq 0 && \text{c.s. b}_{i,r} \geq 0 \\
&\frac{\partial L_i}{\partial \lambda_i} = \overline{W}_i + \sum_r b_{i,r} - w_i A_i + \sum_r s_{i,r} \geq 0 && \text{c.s. } \lambda_i \geq 0 \\
&\frac{\partial L_i}{\partial \delta_i} = \overline{A}_i - A_i \geq 0 && \text{c.s. } \delta_i \geq 0
\end{aligned}
\tag{15}
$$

3.2.2 Municipal and Industrial Problem

Without significant loss of generality, I model the M&I problem as follows: M&I firms begin with an endowment of water and choose to buy water, conservation, and/or new supply up to the point where future demand for water is satisfied with the objective of minimizing total cost. The cost minimization problem for M&I firms is as follows:

$$
\begin{aligned}
&\min_{b_i, C_i, N_i} C_i = \sum_r P_{w,r} b_{i,r} + \sum_r tc_{i,r}(b_{i,r}) + \Omega(C_i) + \Upsilon(N_i) \\
&s.t. \\
&\quad b_{i,r} \geq 0 \\
&\quad d_i \leq \overline{W}_i + \theta \sum_r b_{i,r} + C_i + N_i
\end{aligned}
\tag{16}
$$

where $P_{w,r}$ is price per unit of water bought/sold from regional pool *r*, $b_{i,r}$ is the amount of water bought by firm *i* from regional pool *r*, and $tc_{i,r}(b_{i,r})$ is the total transaction cost as a function of water bought that is incurred by firm *i* from transferring water from regional pool *r*. $\Omega(C)$ is total cost of conserving C units of water, C_i is the quantity of water conserved by M&I firm *i*, $\Upsilon(N)$ is the total cost of purchasing N units of new supply, and N_i is the quantity of new water supply developed by firm *i*. $tc_{i,r} = tcI_{i,r} + tcP_{i,r}$. I assume

$\Upsilon'(\cdot) \geq 0, \Upsilon''(\cdot) \leq 0, \Omega'(\cdot) \geq 0, \Omega''(\cdot) \leq 0$.

d_i is the projected demand for water for firm *i* given current water use and population projections and $\bar{W}_i$ is the total endowment of water for firm *i*, and $0 < \theta \leq 1$ describing the percentage of an average diversion that is considered firm yield[21]. Without loss of generality, upper bounds are not placed on conservation and building new supply, since M&I firms have an incentive to minimize costs (Zhu, Marques, and Lund, 2015). The functional form of the cost functions will determine the point at which conservation/building new supply becomes cost prohibitive. Future demand, firm yield, water availability, cost of conservation, cost of new supply, and transaction costs are exogenously determined while $P_{w,r}$, $b_{i,r}$, C_i, and N_i are endogenously determined.

Resulting in the following Lagrangian:

$$L_i = \sum_r P_{w,r} b_{i,r} + \sum_r tc_{i,r}(b_{i,r}) + \Omega(C_i) + \Upsilon(N_i) + \lambda_i(d_i - \bar{W}_i - \theta \sum_r b_{i,r} - C_i - N_i) \qquad (17)$$

[21] Municipalities are risk averse and generally seek to maintain a steady water supply in the face of varying climatic conditions (Characklis, Griffin, and Bedient, 1999). Thus, the amount of water that it is assumed a water right/water from new supply will yield is not based on average diversions/expected yield, but rather diversions in times of drought (i.e. firm yield).

The solutions to this problem are $P_r, b_{i,r}$, C_i, N_i, and λ_i and satisfy the following first order conditions:

$$\begin{aligned}
&\frac{\partial L_i}{\partial b_{i,r}} = P_w + tc_b(b_{i,r}) - \lambda_i\theta \geq 0 && \text{c.s. } b_{i,r} \geq 0 \\
&\frac{\partial L_i}{\partial C_i} = \Omega_C(C_i) - \lambda_i \geq 0 && \text{c.s. } C_i \geq 0 \\
&\frac{\partial L_i}{\partial N_i} = \Upsilon_N(N_i) - \lambda_i \geq 0 && \text{c.s. } N_i \geq 0 \\
&\frac{\partial L_i}{\partial \lambda_i} = d_i - \bar{W}_i - \theta\sum_r b_{i,r} - C_i - N_i \geq 0 && \text{c.s.} \lambda_i \geq 0
\end{aligned} \tag{18}$$

The amount of water purchased on the water market, conserved and derived from new supply depends on the relative marginal costs of each. It can be assumed that the fourth constraint is binding, where $d_i = \bar{W}_i + \theta\sum_r b_{i,r} + C_i + N_i$, due to the specification of d_i as exogenous determined. Regardless of the solution to the model, M&I firms will acquire/conserve enough water to meet future demands (d_i), and given they are cost minimizers, no extra water will be purchased.

λ_i represents the minimum cost per acre foot of meeting the city's goal of meeting future demand for water. If $\frac{P_w + tc_b(b_{i,r})}{\theta} > \lambda_i$ then no water will be purchased on the water market; i.e., it is more cost effective to meet future demand through conservation and/or building new supply. But if $\frac{P_w + tc_b(b_{i,r})}{\theta} = \lambda_i$, then some amount of water will be purchased on the water market and the quantity purchased will depend on the relative costs of conservation and new supply. If $\Omega_C(C_i) > \lambda_i$ then zero conservation will be purchased as it is too costly relative to the other options by which to meet future demand. If on the other hand, $\Omega_C(C_i) = \lambda_i$, then some amount of conservation will be purchased and that amount depends on the marginal cost of conservation compared to purchasing water on the water market and building new supply. Similarly, if $\Upsilon_N(N_i) > \lambda_i$ then no new supply will be purchased and if $\Upsilon_N(N_i) = \lambda_i$ then some amount of new supply will be purchased.

The amount of water purchased on the water market, conserved and derived from new supply will be such that, if a positive amount of water is purchased for any of the means by which to meet future demand, the quantity demanded will be such that the marginal cost across alternatives is equal. If the marginal cost for one option is greater than that of the other two options, zero units of that option will be chosen. For example, if $b_{i,r}, C_i, N_i > 0$ then $\left[P_w + tc_b(b_{i,r})\right]/\theta = \Omega_C(C_i) = \Upsilon_N(N_i)$.

3.2.3 Market Setting

Producers can buy water from other producers, sell water to other producers, or sell water to M&I firms. M&I firms can only buy water from producers. This is consistent with the empirical research that finds municipalities rarely sell water rights (Howe and Goemans, 2003; Brookshire, Granderton, Colby, 2004). Water is sold into a regional pool and purchased from a regional pool, rather than traded directly between firms. There is a market clearing price for each regional pool which is determined by the total amount of water bought out of and sold into and that regional pool as well as the transaction costs incurred.

The equilibrium is defined by the level of output, quantity of water traded, and price of water that results when producers seek to maximize their profits by choosing the amount of water to use in production, amount of land to use in production, and the amount of water to buy/sell, while at the same time M&I firms seek to minimize the costs of meeting future demand for water (i.e. $w_i, A_i, s_{i,r}, b_{i,r}, \mathrm{C}_i$, N_i, and λ_i). Firms optimize according to their own idiosyncratic production/cost functions. The welfare for producers is measured as the profit for each producer, based on output price, output quantity, cost of output and cost of water, price of water plus transaction costs incurred, and the quantity of water traded. Welfare for M&I firms is measured as the total cost incurred by the water provider, based on price of water plus transaction costs incurred and quantity of water traded. In equilibrium, the amount of water that is purchased by all firms is equal to the amount of water sold.

The market clearing condition for each regional pool, *r*, is defined by:

$$\sum_i b_{i,r} = \sum_i s_{i,r} \tag{19}$$

When the market clears, the total amount of water sold into a regional pool equals the total amount of water bought from the regional pool. Interactions between the firms in the water market determine the market clearing price of water in each regional pool.

3.2.4 Example of Impacts of Conservation and New Supply on Market Equilibrium in a Water Market with Two Regions and Two Types of Firms

The impact of conservation/new supply on the market price of water and quantity of water transferred out of agriculture in each region depends on the profit functions, transaction costs incurred, population growth, relative abundance of water across each region, and the amount of water that can be conserved/yielded from new supply. To illustrate, consider a two-region model in which one region is relatively water poor while the other region is relatively water rich. Figure 15 describes a water market, consisting of two regions, in which demand for water can be met only by purchasing water on the water market, serving as the base case from which to compare; conservation and new supply are not options. The demand for water in Region 1, D_1, can be met by the supply in Region 1, S_1, but the supply in Region 2, S_2, is not adequate to meet demand, D_2. Excess demand in Region 2 is met by Region 1, generating market demand curve, D_M, and a transaction costs is incurred on the water purchased by Region 2 from Region 1, $tc_{2,1}$.

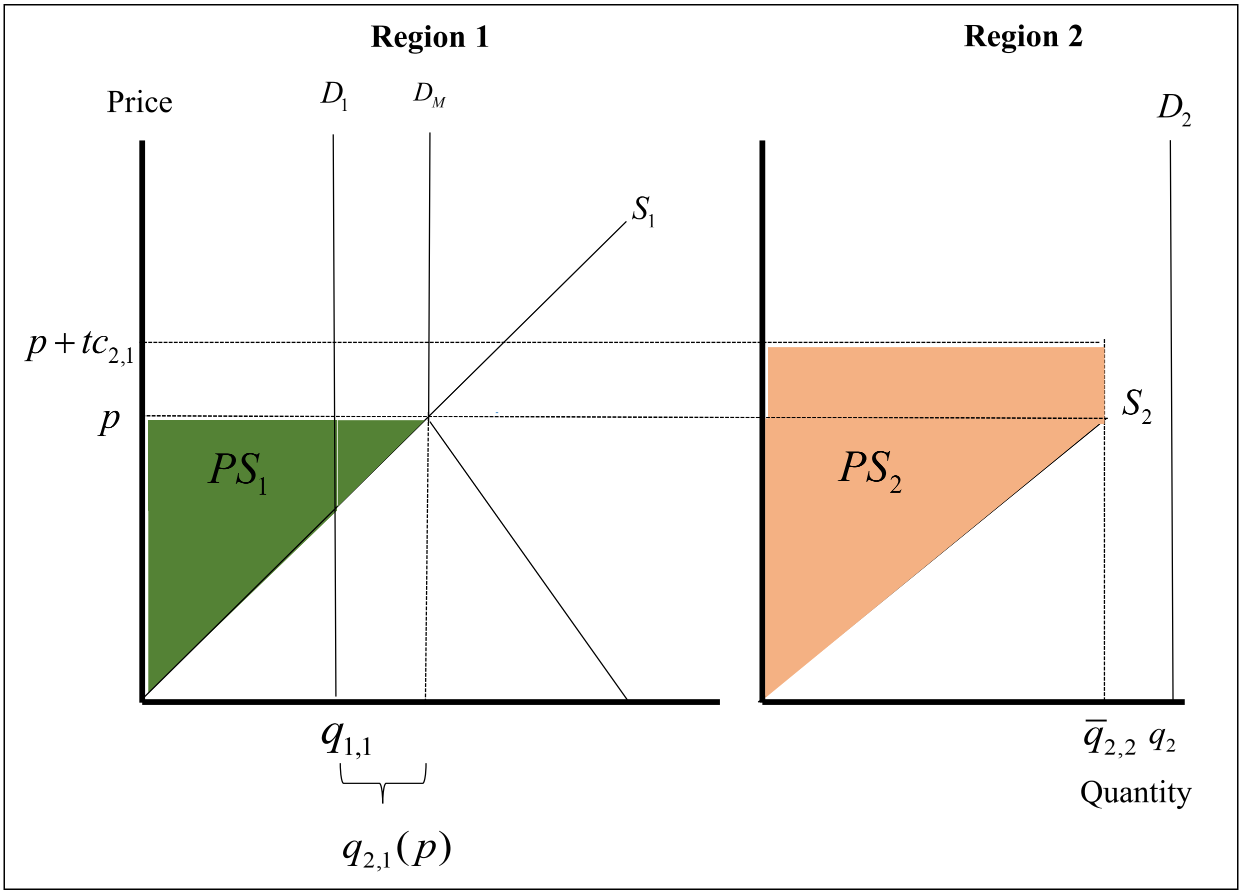

Figure 15. Equilibrium price and quantity and resulting producer welfare in a water market with two regional pools

At any price of water at or above $p+tc_{2,1}$ (the price of water in Region 1 plus transaction costs incurred when Region 2 purchases from Region 1), Region 2 will purchase the maximum possible from within its own region, $\overline{q}_{2,2}$, and fulfill all remaining demand from Region 1, $q_2-\overline{q}_{2,2}$. For any price below $p+tc_{2,1}$, Region 2 will decrease purchases from Region 2 as it is relatively less expensive to buy water from Region 1, $q_{2,2}(p<p+tc_{2,1})<\overline{q}_{2,2}$ and increase purchases from Region 1, $q_{2,1}(p<p+tc_{2,1})>q_{2,1}(p+tc_{2,1})$. In the latter scenario, the amount of water purchased from each region depends on the elasticity of the market demand curve.

Resulting producer surplus for each from the water market is described by PS_1 and PS_2. For more detail on market dynamics and the impact of transaction costs, please see Chapter 2.

For all market demand curves at or to the right of D_M, the price of water in Region 1 will be determined by the intersection of the market demand curve and the supply curve in Region 1, occurring at a price of p or greater and falling on the perfectly inelastic portion of the market demand curve. The price of water in Region 2 will be this intersection plus transaction costs. The market demand curve, D_M, will be kinked at the maximum available supply in Region 2, p, regardless of how far to the right of D_M the market demand curve falls or the level of transaction costs incurred by Region 2.

For market demand curves to the left of D_M, resulting market prices and where the market demand curve is kinked depends on the magnitude of transaction costs incurred by Region 2. The price of water in Region 1 will be determined by the intersection of the market demand curve and the supply curve in Region 1; this intersection will be less than p. The price of water in Region 2 will be the price of water in Region 1 plus transaction costs; if this is greater than or equal to p then the case described in the example above will hold. If not, then the market demand curve will be kinked below p at the price of water in Region 1 plus transaction costs. Note that changes from each of these points on the demand curve (above or below the kink point) will have different implications in the market; these differences will be discussed in the remainder of this section.

Conservation/new supply are introduced into the market and impacts are evaluated; impacts can be due to conservation or new supply, but results will be the same. As is the case in most of the western U.S., it is assumed that at least some portion of gap between forecasted demand and existing supplies will be met by the water market, conservation and/or new supply will only serve to reduce the amount of water purchased on the water market. I provide examples for two scenarios: one, demand for water in Region 2 is such that firms must purchase water from an outside region, even when the maximum allowable conservation and new supply are purchased (Figure 16 and Figure 17); and two, demand for water in Region 2 can be met by a combination of supply from within its own region, conservation, and new supply, no purchases from outside regions are necessary, although could occur depending on relative prices (Figure 18).

3.2.4.1 SCENARIO ONE: INTERREGIONAL TRADING

In Figure 16, in addition to purchasing water on the market, municipalities choose to conserve as a means by which to meet future demand, decreasing demand for water in both regions, but not so much that demand in Region 2 can be met from within the region. Demand for water in Region 1 decreases from D_1 to $D_1{}^C$ and in Region 2 from D_2 to $D_2{}^C$, thus decreasing market demand from D_M to $D_M{}^C$. The price of water in Region 1 decreases from p^* to p^C and the price of water in Region 2 decreases from $p^* + tc_{2,1}$ to $p^C + tc_{2,1}$. Because the price of water in both regions remains above p, there is no change in the quantity of water purchased from Region 2; as is the case without conservation, all available water in Region 2 is purchased from within the region.

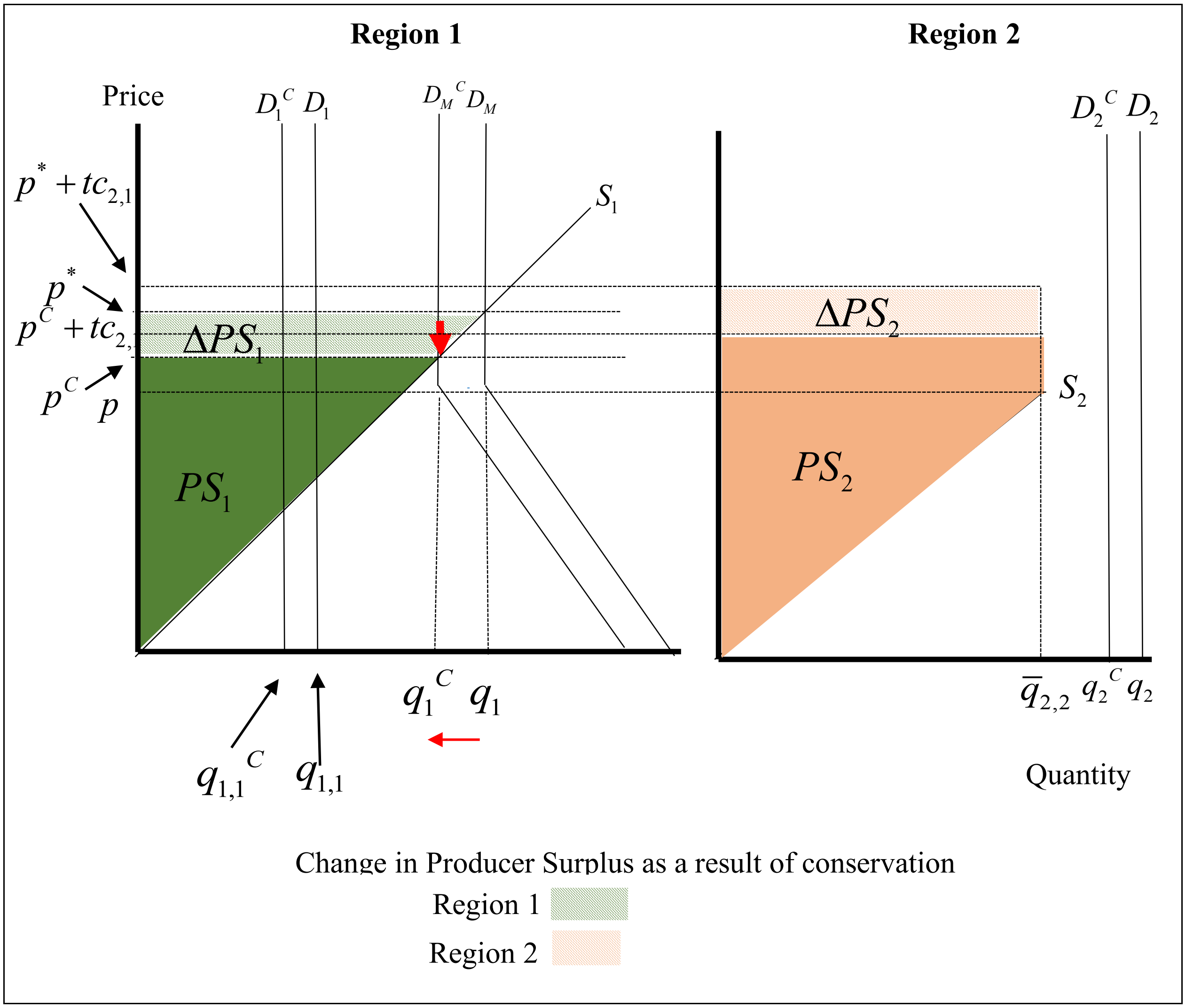

Figure 16. Equilibrium price and quantity and resulting producer welfare in a water market with conservation and two regional pools with interregional trading and $p^C \geq p$

While the quantity of water purchased from Region 2 does not change with the introduction of conservation, it does impact the quantity of water demanded from Region 1, decreasing the price of water in Region 2, and thus decreasing regional profits. When $p^C > p$, conservation leads to a decrease in producer surplus resulting from the water market in both regions. Note that the change in welfare described here is for the water market only. The decrease in the market demand for water means that more water will remain in production, leading to an increase in welfare from production; those, potentially offsetting, impacts are not captured in this discussion.

The next example is of a market in which the introduction of conservation decreases demand such that the price of water in Region 1 is below p, decreasing from p to p^C. Contrary to the previous example, the transaction costs incurred by Region 2 when purchasing water from Region 1 will impact the quantity of water purchased from each region. If $p^C + tc_{2,1} \geq p$, then results will follow the market dynamics described in the previous figure. If, on the other hand, $p^C + tc_{2,1} < p$, then market dynamics will occur as described in Figure 17.

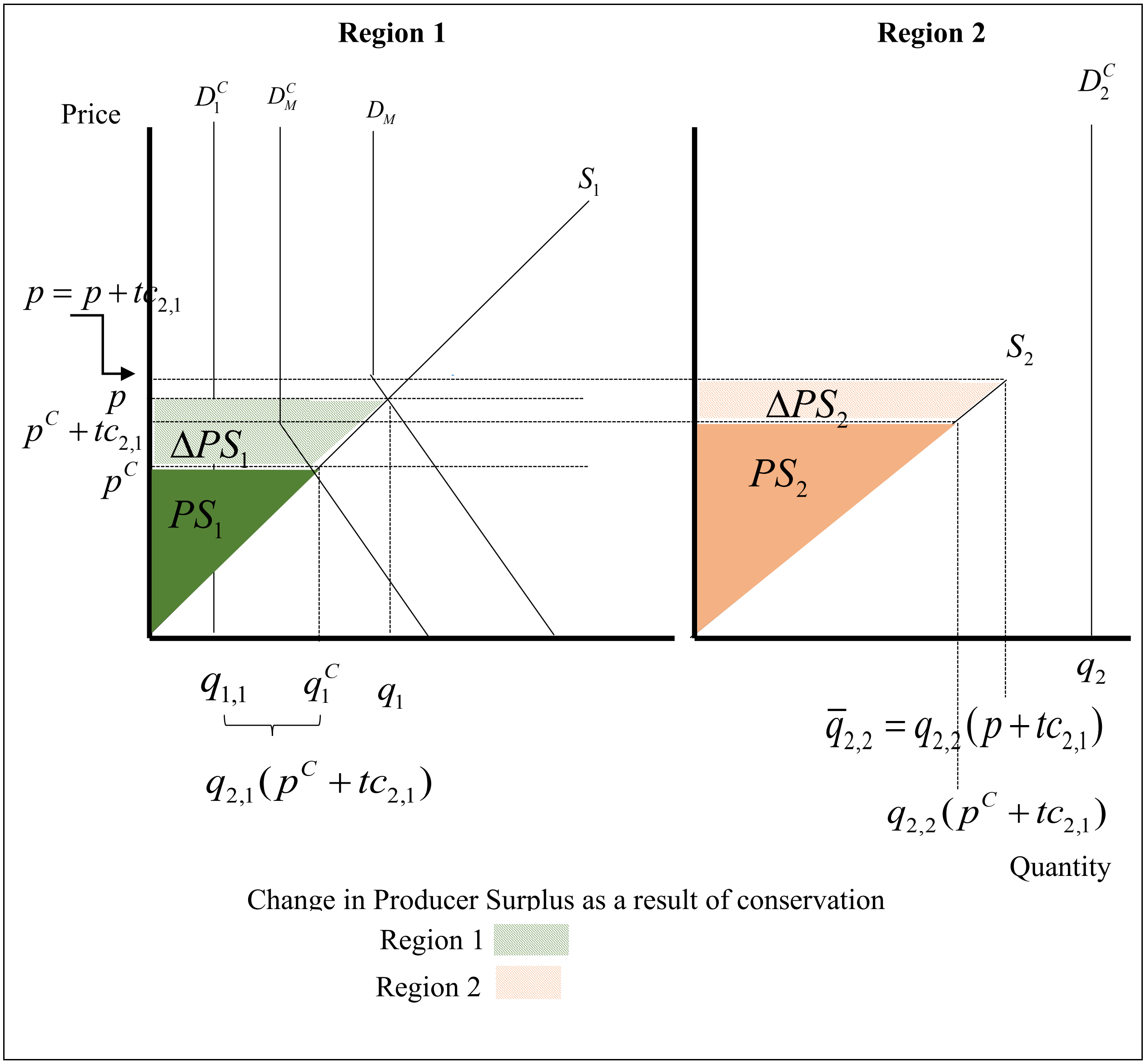

Figure 17. Equilibrium price and quantity and resulting producer welfare in a water market with conservation and two regional pools with interregional trading and $p^C + tc_{2,1} < p$

Conservation decreases demand, shifting the market demand curve to the left from D_M to D_M^C, causing the price of water in Region 1 to decrease from p to p^C, the total quantity of water demanded from Region 1 to decrease from q_1 to q_1^C, and the price in Region 2 to shift from $p + tc_{2,1}$ (which in this example is equivalent to p) to $p^C + tc_{2,1}$. When the price of water in Region 1 plus transaction cost is less than p, municipalities in Region 2 do not purchase all available water in their own region, they want to purchase more water from Region 1 as it is relatively less expensive. This decreases the quantity of water demanded from Region 2 downward from $\bar{q}_{2,2}$ to $q_{2,2}(p^C + tc_{2,1})$. When $p^C + tc_{2,1} < p$, producer surplus from the water market decreases in both regions as a result of conservation, shown by ΔPS_1 and ΔPS_2.

3.2.4.2 SCENARIO TWO: NO INTERREGIONAL TRADING

Figure 18 describes a market in which the introduction of conservation decreases demand such that Region 2 no longer purchases water from Region 1 in order to meet demand. Demand for water in Region 1 decreases from D_1 to D_1^C and in Region 2 from D_2 to D_2^C, thus decreasing market demand from D_M to D_M^C. As described above, implications of conservation will depend on the price of water in Region 2 relative to p. In this example, the price of water in Region 2 is greater than p, $p_1 + tc_{2,1} \geq p$, thus Region 2 is better off buying all necessary water from within their own region and there will be no interregional trading. Producers in Region 1 will receive p_1 and producers in Region 2 will receive p_2 for each unit of water sold on the market, where p_1 and p_2 are determined by the supply and demand in each region.

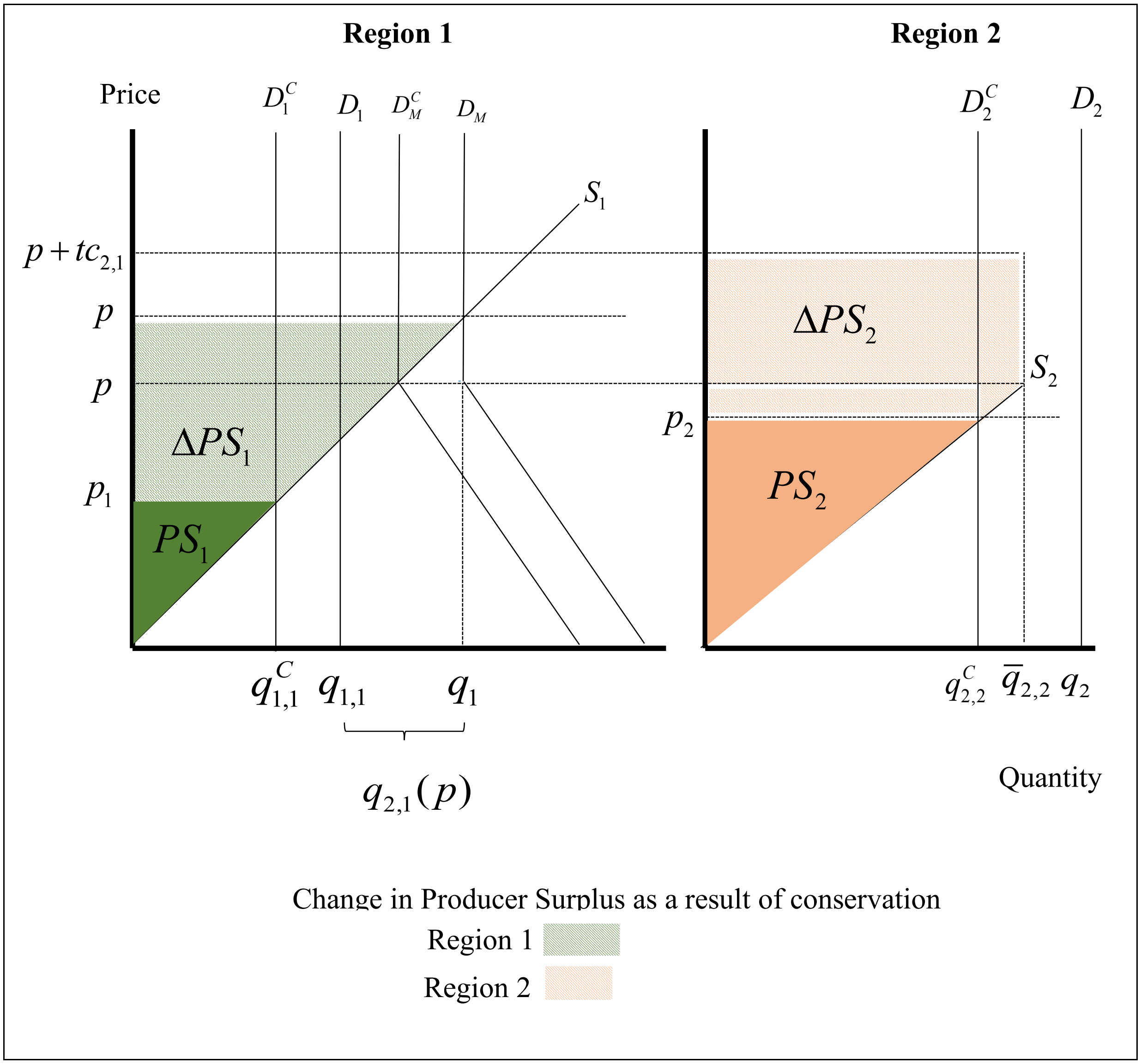

Figure 18. Equilibrium price and quantity and resulting producer welfare in a water market with conservation and two regional pools with no interregional trading

Before the introduction of conservation, producers in Region 2 were able to charge $p + tc_{2,1}$ because they knew that firms in their own region were willing to spend that amount of money to acquire water (as shown by purchases from Region 1). With the introduction of conservation, demand decreased such that Region 2 no longer had to purchase water from an outside region, decreasing the price that producers in Region 2 could charge from $p + tc_{2,1}$ to p_2

and the quantity sold from $\bar{q}_{2,2}$ to $q^{C}_{2,2}$. When conservation/new supply decreases the quantity of water demanded such that no interregional trading is necessary, significant changes in market dynamics could occur based on the relative price of water in each region. Compared to the previous scenarios, decreases in producer surplus from the water market are larger in both regions when there is no interregional trading.

If the price of water in Region 2 is such that firms are better off not purchasing water from an outside region, producers in both regions see a significant decrease in producer surplus from the water market. Note that because less water is purchased on the market, these same producers also see an increase in welfare from production, potentially offsetting a portion of the losses incurred on the market; these dynamics are not included in the figures discussed in this section. If the price of water in Region 2 is less than p, $p_1 + tc_{2,1} < p$, then Region 2 will purchase some water from Region 1 as it is relatively less expensive than purchasing from Region 1. Market dynamics will be the same as described in Figure 17.

3.3 Model Parameterization

The calibrated model and data presented in Chapter 2 are utilized in this model with data additions for conservation and new supply. All data on conservation costs and quantities as well as new supply costs and quantities comes from SWSI (2010), Colorado's statewide water plan. The section will begin with a brief description of the region used in this study, followed by a description of conservation and by new supply data. For a full description of the data used and calibration methods, see Chapter 2.

Figure 19 is a map of the South Platte River basin divided into five regions. The Central region includes Adams, Arapahoe, Clear Creek, Denver, Gilpin, and Jefferson counties and is characterized by large municipal firms and some agricultural firms. The South Metro region includes Douglas, Elbert, and Park and is characterized by municipal firms that utilize ground water and no agricultural producers[22]. The East is the final region and includes Morgan, Logan, Sedgwick, and Washington and is characterized by having only agricultural firms. Regions are defined such that counties with similar water access are grouped together, enabling the inclusion of the heterogeneous transaction costs associated with transferring water.

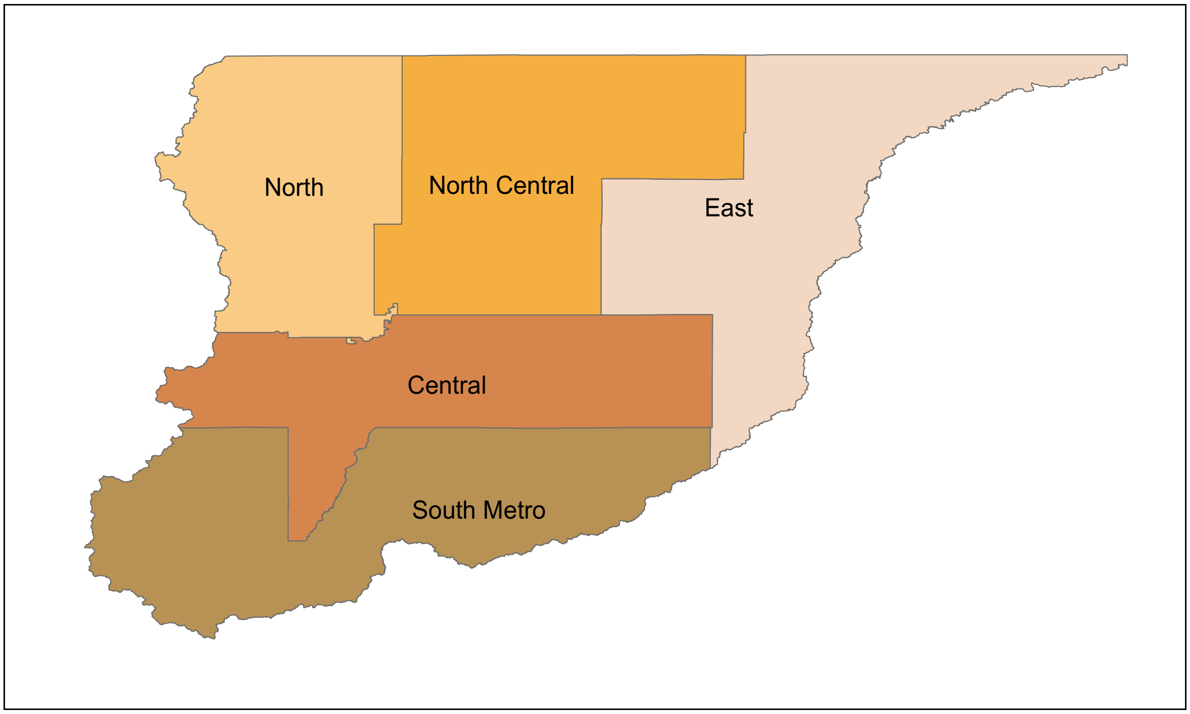

Figure 19. Map of the South Platte River Basin Divided into Five Regions

There are two types of transaction costs, physical and institutional. Physical transaction costs vary across regions whereas institutional transaction costs do not. When a municipality purchases water from within their own region, they incur only institutional transaction costs of $5,000 per acre foot. When purchasing from an outside region, a municipality incurs both a physical and institutional transaction cost, ranging from $15,000 to $35,000 per acre foot (Table 15). The cost of purchasing water is the price of water in the region from which water is being purchased plus the transaction costs associated with that transfer.

[22] There are a small number of producers in this region, but those enterprises mostly produce grass pasture and are therefore not included in this model.

Table 15. Transaction costs associated with purchasing water (per acre foot)

	North	North Central	Central	East
North	$5,000	$25,000	$25,000	$35,000
North Central	$15,000	$5,000	$25,000	$25,000
Central	$25,000	$25,000	$5,000	$25,000
South Metro[23]	$35,000	$35,000	$25,000	$25,000
East	$15,000	$15,00	$15,000	$5,000

Rows are buyers and columns are regional pool from which they are purchasing

There are two types of conservation, passive and active. Passive conservation is conservation that is going to occur based on the regulatory changes in place for new and existing construction. It is assumed that passive conservation has zero cost as it will happen regardless of the actions taken by municipalities. Because passive conservation is costless, municipalities will choose to conserve the maximum allowable passive conservation. Future demand is essentially reduced by the maximum allowable passive conservation. Active conservation, on the other hand, has associated costs.

In the SWSI (2010) report, three active conservation strategies are presented (low, medium and high) along with their associated costs and conservation amounts. For more details on these scenarios and the assumptions behind them, please see SWSI (2010). Water savings resulting from conservation and the associated costs per acre foot were calculated on a statewide level. Water savings as a percent of 2050 water demand are presented in Table 16, ranging from 9% of 2050 demand met through passive conservation up to 35% of 2050 demand meet through active conservation, assuming the most aggressive water saving strategy. Costs of conservation are presented in Table 17, with active conservation costs ranging from around $5,000 to $8,000 per acre foot conserved.

[23] Note that because there is no water in the South Metro region, transaction costs are only for the South Metro purchasing water from other regions.

Table 16. Water savings as a percent of 2050 demand, statewide

	Low water saving strategy	**Medium water saving strategy**	**High water saving strategy**
Passive	9%	9%	9%
Active	9%	19%	26%
Total	18%	28%	35%

Source: SWSI (2010)

Table 17. Estimated cost per acre foot

	Low water saving strategy	**Medium water saving strategy**	**High water saving strategy**
Passive	\$0	\$0	\$0
Active	\$5,358	\$7,296	\$8,183
Total	\$5,358	\$7,296	\$8,183

Source: SWSI (2010)

Rather than analyzing each conservation scenario separately, given the relatively low cost of conservation compared to purchasing water on the market or building new supply, I assume M&I firms will choose to conserve the maximum allowable and thus incur costs associated with the high water saving strategy. To calculate the maximum quantity of water that could be saved under each water saving strategy for each of the five regions in the South Platte River Basin, the conservations saving percentages from Table 16 were applied to the consumptively used portion of 2050 demand in each of the five regions. The resulting maximum amount of water savings through conservation for each region are presented in Table 18.

Table 18. Maximum savings from conservation (acre feet)

Region	Passive conservation	Low water saving strategy	Medium water saving strategy	High water saving strategy
North	1,608	1,673	3,459	4,818
North Central	1,451	1,509	3,121	4,346
Central	3,872	4,028	8,328	11,599
South Metro	996	1,037	2,143	2,985
East	227	236	489	681

To limit conservation to a realistic quantity, one can impose an upper bound (Zhu, Marques, and Lund, 2015), which in this case would be the quantity conserved in the high water saving strategy. Or, the estimated cost function can be calibrated such that municipalities choose to conserve close to the quantity conserved in the high water saving strategy but no upper bound is imposed. For the purposes of this study, an upper bound on conservation is imposed based on the high water saving strategy.

The associated cost and water yields from building new supply are also taken from the SWSI (2010) report. This report describes new supply based on identified projects and processes (IPP's), defined as water provider's predictions of the quantity of water that will be provided through new water supply from identified projects and processes. In the SWSI (2010) report, the region that is called the South Platte River Basin in this study is divided into two basins, called the South Platte River Basin and the Metro Basin.

I assume that the SWSI new supply yield for the South Platte River basin is split between the North and North Central regions based on long run demand projections and the new supply yield for the Metro Basin is split between the Central and South Metro regions based on long run demand projections. Zero new supply is allotted to the East region[24]. Yields resulting from IPP's are presented in Table 19 with total estimated yield of IPP's (not including water transfers) for the basin of 221,000 acre feet. All IPP's listed in Table 19 have an estimated cost of $14,000 per acre foot, with the exception of "new transbasin project" which has an average cost of $30,000. When included in the modeling framework, IPP yields presented are converted to consumptive use by multiplying the yield by 20%.

Table 19. Yields from identified projects and processes (IPP's) assuming the low scenario and 100% success rate (AFY)

Basin	**Reuse**	**Growth in existing supplies**	**Regional in-basin project**	**New trans-basin project**	**Firming in basin water rights**	**Firming trans-basin water rights**	**Total IPP's (not including transfers)**
Metro	14,000	55,000	34,000	13,000	900	3,500	120,000
South Platte	5,000	20,000	37,000	0	22,000	18,000	101,000
Total	19,000	75,000	71,000	13,000	22,900	21,500	221,000

Source: SWSI (2010, Table 5-1)

To compare the different means by which future demand for water can be met, the consumptively used portion of water needed to meet future demands, available water supplies, quantity of water that can be conserved, and the yields from new supply are presented in Table 20. Future demand for water can be met fully by water on the water market (272,000 acre feet are available and 93,000 are demanded), but due to the relatively high cost of purchasing water on the water market ($22,000 to $48,000) compared to conservation and new supply ($8,000 to $30,000), fulfilling 100 percent of future demand through water market purchases will not be a cost minimizing strategy. While conservation and new supply are relatively less expensive,

[24] The East region has excess supply to meet future demand for water and therefore would not invest in new supply projects.

together, they can provide a maximum of 77,000 acre feet of water, falling short of future demand by 16,000 acre feet. Future demand will be met by a combination of water purchases on the market, conservation and building new supply; the amount purchased of each option will depend on relative prices and maximum available water.

Table 20. 2050 municipal water demand minus current water supply, maximum savings from conservation, maximum yields from new supply, and associated costs; all numbers reflect the consumptively used portion of water (AFY)

Region	2050 municipal demand - current water supply	Maximum yield from water market[25]	Maximum savings from passive conservation	Maximum savings from active conservation	Maximum yield from new in-basin supply	Maximum yield from new trans-basin supply
North	18,400	104,349	1,608	4,818	10,619	0
North Central	16,600	83,508	1,451	4,346	9,581	0
Central	44,300	31,263	3,872	11,599	17,020	2,068
South Metro	11,400	0	996	2,985	4,380	532
East	2,600	53,087	227	681	0	0
Total	**93,000**	**272,207**	**8,155**	**24,429**	**41,600**	**2,600**
Cost		$21,000 to $48,000[26]	$0	$8,000	$14,000	$30,000

[25] Note that there is a conversion factor of 0.7, to convert water used in agriculture into firm yield bought by municipalities. Every one acre foot of water purchased by a municipality yields 0.7 acre feet to meet long run demand. This is not accounted for in the numbers presented here, but is included in the M&I problem.

[26] Cost per acre foot of water purchased on the market are based on the results presented in Chapter 2.

3.3.1 Model Impacts

To evaluate the impact of utilizing a portfolio approach on the cost for municipalities to acquire water to meet long run demand, the model is run for four scenarios: (1) water market only (base case), (2) water market and conservation only, (3) water market and new supply development only, (4) water market, conservation, and new supply development. To evaluate the impacts from a portfolio approach to meeting future demand for water, these scenarios will be run with a focus on four impacts:

1. *M&I.* I evaluate the impact of conservation and new supply development on the cost per acre foot for M&I firms to meet the supply gap and why this impact changes under differing maximum allowable conservation and news supply scenarios. I describe the cost per acre foot and quantity of water transferred and average cost per acre foot acquired.
2. *Producers.* I evaluate the impact of conservation and new supply on producers, including total profits (from production and the sale of water rights), who wins and who loses, and why these changes occur.
3. *Different levels of conservation versus different levels of new supply.* I evaluate the impact of different combinations of the maximum allowable conservation and new supply on producer profits. Maximum allowable conservation and new supply are decreased in 20% increments from 100% to 0% and resulting producer profits from all combinations of maximum allowable new supply and conservation are presented.
4. *Regional.* I estimate how regional economies will change as a result of a portfolio approach to meeting future demand for water.

3.4 Results

Results from the four impacts evaluated in this chapter demonstrate that utilizing a portfolio approach to meeting future demand for water, compared to utilizing a water market only, reduces the cost for M&I firms to acquire water, decreases producer profits from the water market, increases producer profits from production, and decreases economic impacts to rural economies. Conservation and new supply development lead to little to no change in profits for some producers but a reduction in profits for others. Impacts vary depending on the individual characteristics of each firm, including where they are located, the transaction costs incurred as a result of purchasing water, producer participation in the water market, as well as when maximum allowable quantity of water conserved/yielded is varied.

3.4.1 M&I Impacts

To evaluate the impacts of a portfolio approach on M&I firms, I begin with results of the cost per acre foot of water transferred on the market and the quantity of water transferred on the market, evaluating how and why the water market changes with the introduction of conservation and new supply. I conclude the M&I impact section with results of the overall cost per acre foot to meet future demand for water, evaluating how overall costs as well as the composition of costs change with the introduction of conservation and new supply.

When M&I firms utilize only the water market to meet future demand for water, the average price per acre foot to purchase water in the South Platte River Basin is $35,000 (Table 21). Water rich regions (North, North Central, East) have costs ranging from $21,000 to $28,000 while water poor regions with high population growth (Central, South Metro) have costs ranging from $41,000 to $48,000. The higher costs associated with Central and South Metro are largely due to the transaction costs incurred, as both regions purchase water from an outside region.

Table 21. Cost per acre foot for municipalities to acquire water on the water market with and without conservation and new supply, assuming long run population growth and transaction costs

Region	Water Market Only	Maximum Conservation No New Supply	Maximum New Supply No Conservation	Maximum New Supply and Conservation
North	$24,000	$24,000	$22,000	$22,000
North Central	$21,000	$21,000	$20,000	$19,000
Central	$41,000	$41,000	$28,000	$20,000
South Metro	$48,000	$48,000	$48,000	$40,000
East	$28,000	$28,000	$28,000	$24,000
Average	**$35,000**	**$34,000**	**$29,000**	**$23,000**

Compared to the case with the water market only, introducing conservation leads to a decrease in the average cost per acre foot to purchase water on the water market in order to meet long run population growth of around 1%, decreasing from $35,000 per acre foot to $34,000 per acre foot. North, South Metro, and East see no change in the cost to acquire water on the market while North Central and Central see a small decrease. As was the case with a water market only, water rich regions (North, North Central, and East) have lower costs to acquire water than water poor regions with high population growth (Central and South Metro).

The introduction of new supply leads to a larger decrease in the cost to acquire water than does conservation, leading to an average decrease of 17% compared to the case with the water market only, decreasing from $35,000 to $29,000. South Metro and East see no decrease in cost, North and North Central see a modest decrease of 3% and 7%, respectively, and Central sees the largest decrease at 32%. When both new supply and conservation are utilized as a means by which to meet future demand, M&I costs to acquire water are the lowest of all scenarios, with total costs decreasing from $35,000 to $23,000 per acre foot. All regions see a decrease in costs and, as was the case with the introduction of new supply, Central sees the largest decrease, with cost per acre foot decreasing by 51% from $41,000 to $20,000.

To demonstrate why costs differ when conservation is introduced versus new supply and why impacts differ across regions, I evaluate the two components of the cost to purchase water on the market: the quantity of water purchased from each region and price paid (which includes the regional price of water plus transaction costs incurred). Table 22 shows the quantity of water purchased by each region (row), from each region (column). When purchasing water from within a region, M&I firms only incur small transaction costs, but when purchasing from an outside region they incur a much larger transaction costs that differ depending on the location of the buyer and seller. When M&I firms can only utilize the water market to meet future demand for water, Central purchases all available water in their own region (31,000 acre feet) as well as an additional water from North Central, incurring large transaction costs on the 27,000 acre feet purchased from North Central. South Metro does not have any water to purchase from within its own region so it purchases 15,000 acre feet from East and incurs large transaction costs. All other regions fulfill demand from within their own region, only incurring small transaction costs.

Table 22. Water purchased on the market, where the row is the purchasing region and the column is the region from which water is purchased

Water market only

	North	North Central	Central	South Metro	East
North	24,000	0	0	0	0
North Central	0	22,000	0	0	0
Central	0	27,000	31,000	0	0
South Metro	0	0	0	0	15,000
East	0	0	0	0	3,000

Water market and conservation

	North	North Central	Central	South Metro	East
North	17,000	0	0	0	0
North Central	0	15,000	0	0	0
Central	0	10,000	31,000	0	0
South Metro	0	0	0	0	11,000
East	0	0	0	0	2,000

Water market and new supply

	North	North Central	Central	South Metro	East
North	9,000	0	0	0	0
North Central	0	8,000	0	0	0
Central	0	0	31,000	0	0
South Metro	0	0	1,000	0	7,000
East	0	0	0	0	3,000

Water market, conservation, and new supply

	North	North Central	Central	South Metro	East
North	2,000	0	0	0	0
North Central	0	2,000	0	0	0
Central	0	0	17,000	0	0
South Metro	0	0	4,000	0	0
East	0	0	0	0	2,000

The introduction of conservation leads to a decrease in the total quantity of water purchased from each region, but does not shift the regions from which water is purchased, leading to small changes in the cost to acquire water. New supply development, on the other hand, enables Central to meet all of its demand from within its own region. Central no longer purchases from North Central nor incurs large transaction costs; the same dynamic as described in Figure 18 in which interregional trading between the two regions ceases and the regional price and quantity purchased from each region simply depend on supply and demand within each region. Additionally, East shifts some of its water purchases from East to Central due to the lower transaction costs associated with purchasing from Central compared to East. When M&I firms can utilize all three means by which to meet future demands, total demand in the water market decreases for each region. South Metro shifts to purchasing all water from Central, rather than from both East and Central and, as previously, Central purchases all needed water from within its region.

I now move onto the second component of the cost to acquire water on the market: the price paid, which includes the price per acre foot of water in each region plus transaction costs incurred. The introduction of conservation leads to a very minimal decrease in the regional price of water for any region (Table 23). The introduction of new supply leads to no change in East, a \$500 per acre foot decrease in North Central, a \$1,800 per acre foot decrease in North, and a \$13,300 decrease in Central. When all three means by which to meet future demand are available, compared to the water market only, the regional price of water per acre foot in North decreases by \$1,000, in North Central decrease by \$1,700, in Central decreases by \$21,100, and in East decreases by \$4,200.

Table 23. Price of water per acre foot received by seller comparing a water market only to a water market with the option of conservation and new supply development

Regional Pool	Water Market Only	Maximum Conservation No New Supply	Maximum New Supply No Conservation	Maximum New Supply and Conservation
North	$19,100	$19,000	$17,300	$17,100
North Central	$16,000	$15,500	$15,300	$14,300
Central	$36,000	$35,500	$22,700	$14,900
East	$22,700	$22,700	$22,700	$18,500

As conservation and new supply are introduced into the water market, the quantity of water bought and sold from/to each regional pool decreases but does not necessarily lead to a lower price of water in each region. Why is this the case? The price of water received by the seller in each region is driven by the marginal value of water in production as well as transaction costs (for those regions engaged in trading). Given a specified production function, each producer chooses the quantity of water to use on each acre constrained by an upper bound, total number of acres, and quantity of water bought/sold. In all models run, producers choose to use the upper bound of water use per acre or close to it, thus limiting the variance of the marginal value of an acre foot of water in production. The second component of the price of water received by the seller is transaction costs. If a firm in a region purchases from an outside region, they pay the price of water in the region plus transaction cost. The producers in their own region know that this is M&I firms' willingness to pay for water and thus are able to charge the same price for water; transaction costs lead to an increase in the price of water received by sellers.

The introduction of conservation does not lead to a change in the price of water received by the seller. Driven by the small variance of the marginal value of an acre foot of water in production and the fact that conservation does not change transaction costs incurred, leading to small average decrease in the cost to acquire water on the market. The introduction of new supply, on the other hand, does cause a decrease in the price of water for most regions. A modest decrease is seen in water rich regions (North and North Central), driven by the marginal value of water in production and a larger decrease is seen in water poor regions with high population growth with access to water from within their own region (Central), largely driven by transaction costs. Since firms in Central no longer purchase from an outside region nor incur transaction costs, producers in their own region are not able to charge as high a price for water in their own region. The decrease in cost coupled with a smaller quantity purchased leads to a large decrease in the cost to acquire water on the market in Central. East has no option to purchase new supply and thus the price of water remains unchanged. Similar dynamics as those described here occur when all three options by which to meet future demand are utilized.

In the South Platte River Basin, compared to the case with the water market only, introducing conservation leads to a decrease in the average cost per acre foot to acquire water in order to meet long run population growth of around 17%, decreasing from $34,500 per acre foot to $28,500 per acre foot (Table 24). All municipalities are able to save the proportionally the same amount of water across regions as well as face the same conservation cost per acre foot, resulting in similar savings across regions, ranging from 15% to 18%. The cost per acre foot to acquire water with conservation as an option is the lowest for water rich regions that do not purchase water from an outside region, and thus do not incur transaction costs, ranging from $17,800 to $23,400 (North Central, North, East) and then increases to a range of $33,400 to $39,000 (Central, South Metro) for water scarce regions that do purchase water from an outside region, and thus incur transaction costs. As suggested by proponents, conservation leads to a decrease in M&I costs to acquire water to meet future demand.

Table 24. Average cost per acre foot for municipalities to acquire water with and without conservation and new supply, assuming long run population growth and transaction costs

Region	Water Market Only	Maximum Conservation No New Supply	Maximum New Supply No Conservation	Maximum New Supply and Conservation
North	$24,100	$20,600	$17,800	$13,300
North Central	$21,000	$17,800	$16,900	$13,000
Central	$41,000	$33,400	$23,100	$14,100
South Metro	$47,700	$39,000	$35,400	$21,300
East	$27,700	$23,400	$27,700	$20,200
Average	**$34,500**	**$28,500**	**$22,700**	**$14,800**

New supply development, compared to the water market only, leads to an average decrease of 34% in the cost to acquire water for M&I firms in the South Platte River Basin, decreasing from $34,500 to $22,700. Across the regions, prices range from $16,900 (North Central) to $35,400 (South Metro), with all regions seeing savings with the exception of East, which does not have access to new supply development. North Central sees a 20% decrease in the cost per acre foot, North and South Metro both see a 26% decrease, and Central sees a 44% decrease. Compared to conservation, new supply leads to a larger decrease in the cost to acquire water, even with the higher cost associated with new supply development. Utilizing all three means by which to meet future demand leads to the largest reduction in the average cost to acquire water, with costs basin-wide decreasing by 57%. Compared to the cost of purchasing water on the market, the average total cost to acquire water is lower for all scenarios in which conservation and/or new supply are available.

Figure 20 shows the allocation of total costs across the different means by which to meet future demand. When conservation is introduced, only a small portion of costs are spent on conservation (6%), the remaining costs are incurred through purchases made on the water market. As new supply is introduced, a larger portion of costs is devoted to new supply (28%), although the water market remains the dominant cost to acquire water (72%). In the last scenario in which both new supply and conservation are utilized, 14% of costs are devoted to conservation with new supply and the water market taking equal portions of the remaining costs to acquire water. The portfolio approach to acquiring water to meet future demands results in fewer transactions taking place on the water market, resulting in a diversification of costs spent to acquire water.

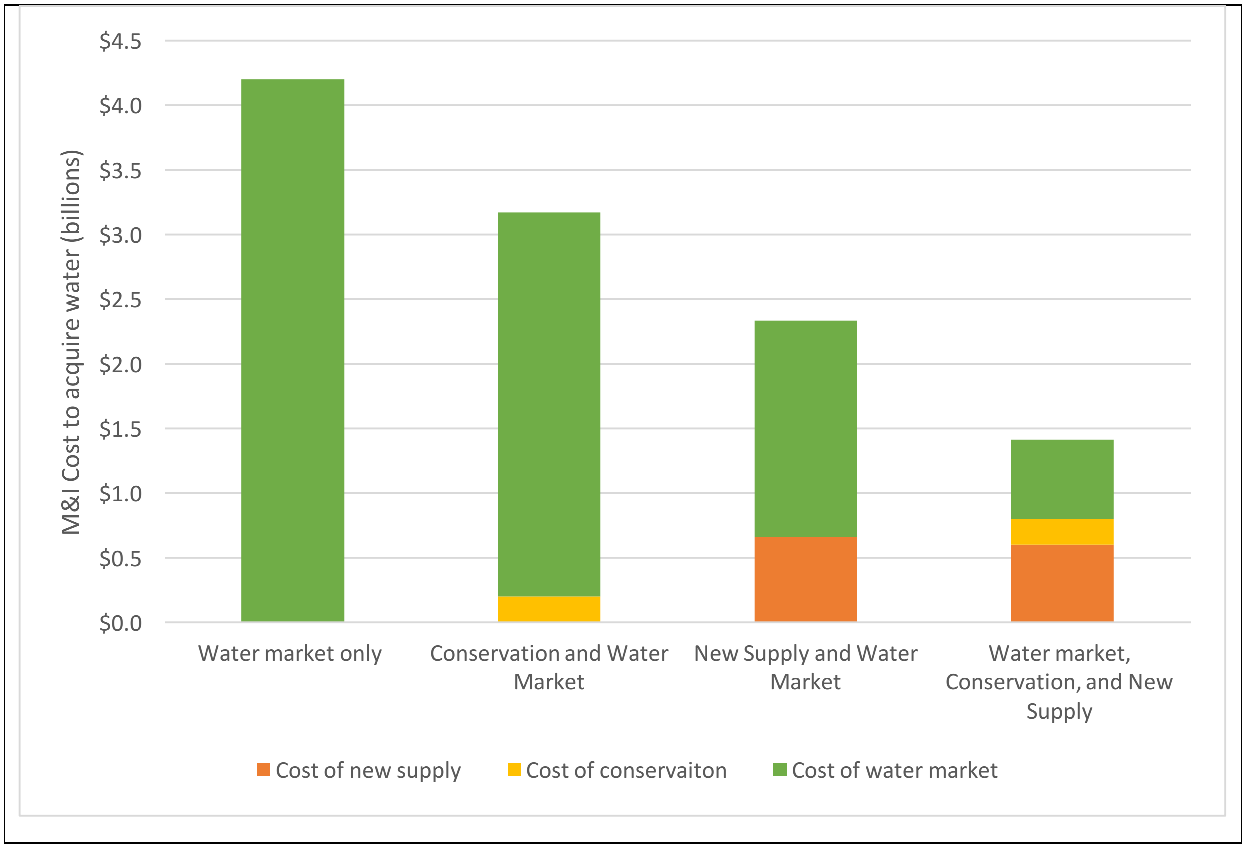

Figure 20. M&I total cost to acquire water to meet future demands with and without conservation and new supply, assuming long run population growth and transaction costs

3.4.2 Producer Impacts

The discussion of producer impacts begins with producer profits resulting from the water market in which M&I firms have the option of conservation, a water market in which M&I firms have the option of new supply development, and when M&I firms utilize a portfolio approach to meet future demand for water. A discussion of who wins and who loses and why these changes occur follows.

When M&I firms utilize the water market only to meet future demand for water, total producer profits in the South Platte River Basin are $5.8 billion, with slightly over half of profits coming from production (53%) and the remaining from the water market (47%) (Figure 21). With the introduction of conservation, while total profits decrease only slightly (1%), the composition of profits sees a larger change; a higher portion of total profits are earned from production (63%) than from the water market (37%). The introduction of new supply development leads to a decrease in profit from $5.8 billion to $5.4 billion and a further shift of total profits towards profits earned from production (77%) and away from profits earned on the water market (33%). When M&I firms can utilize all three options by which to meet future demand, total profits decrease from $5.8 billion to $5.1 billion, with almost all profits earned from production (92%) and the remaining earned on the water market (8%). The decreased demand for water as a result of conservation and new supply leads to a decrease in producer profits in the South Platte River Basin, albeit small in the case of conservation.

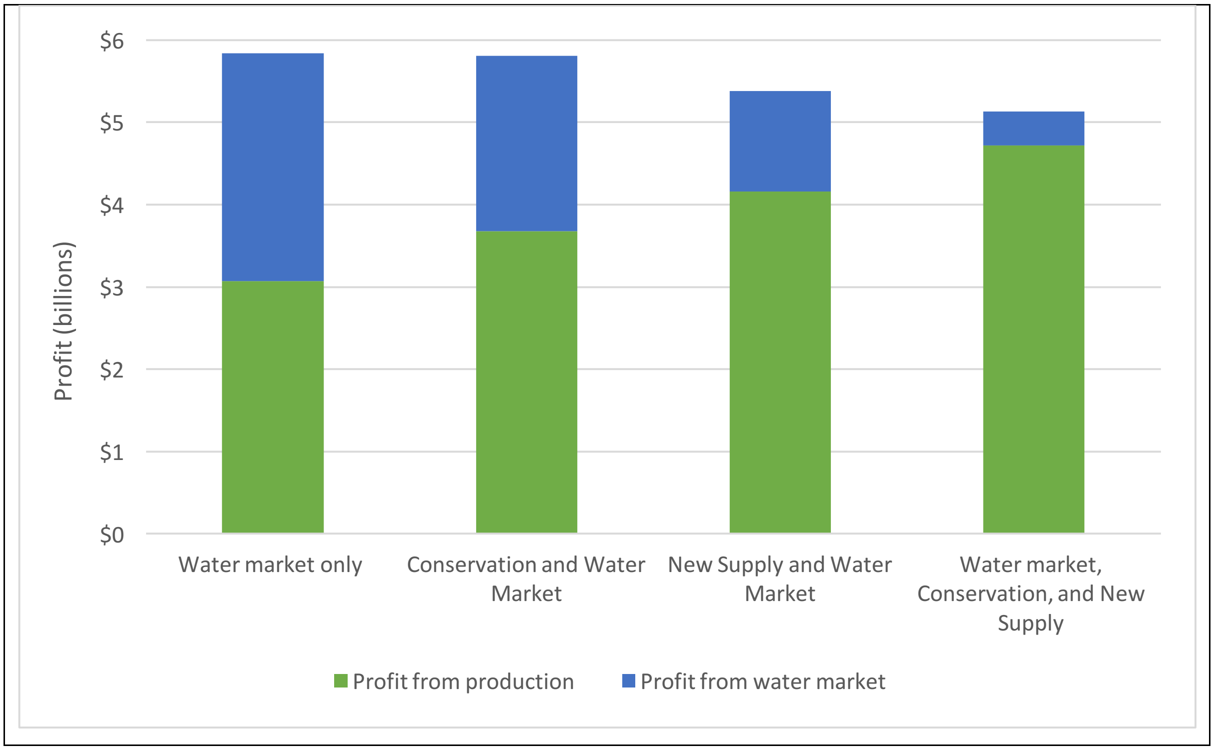

Figure 21. Total producer profit from production and the water market with and without conservation and new supply, assuming long run population growth and transaction costs

Next, changes in profit by region are evaluated, demonstrating the regional differences driving basin-wide changes. Total producer profits in all regions, with the exception of Central, remain virtually unchanged across scenarios (Figure 22). It is the producers in Central, a water poor region with high population growth, that drive the decrease in total profits as a result of introducing conservation and new supply on the water market. The decrease in profits occurs when new supply is introduced, with profits in Central decreasing from $1.1 billion to $700 million and down further to $500 million when both new supply and conservation are utilized.

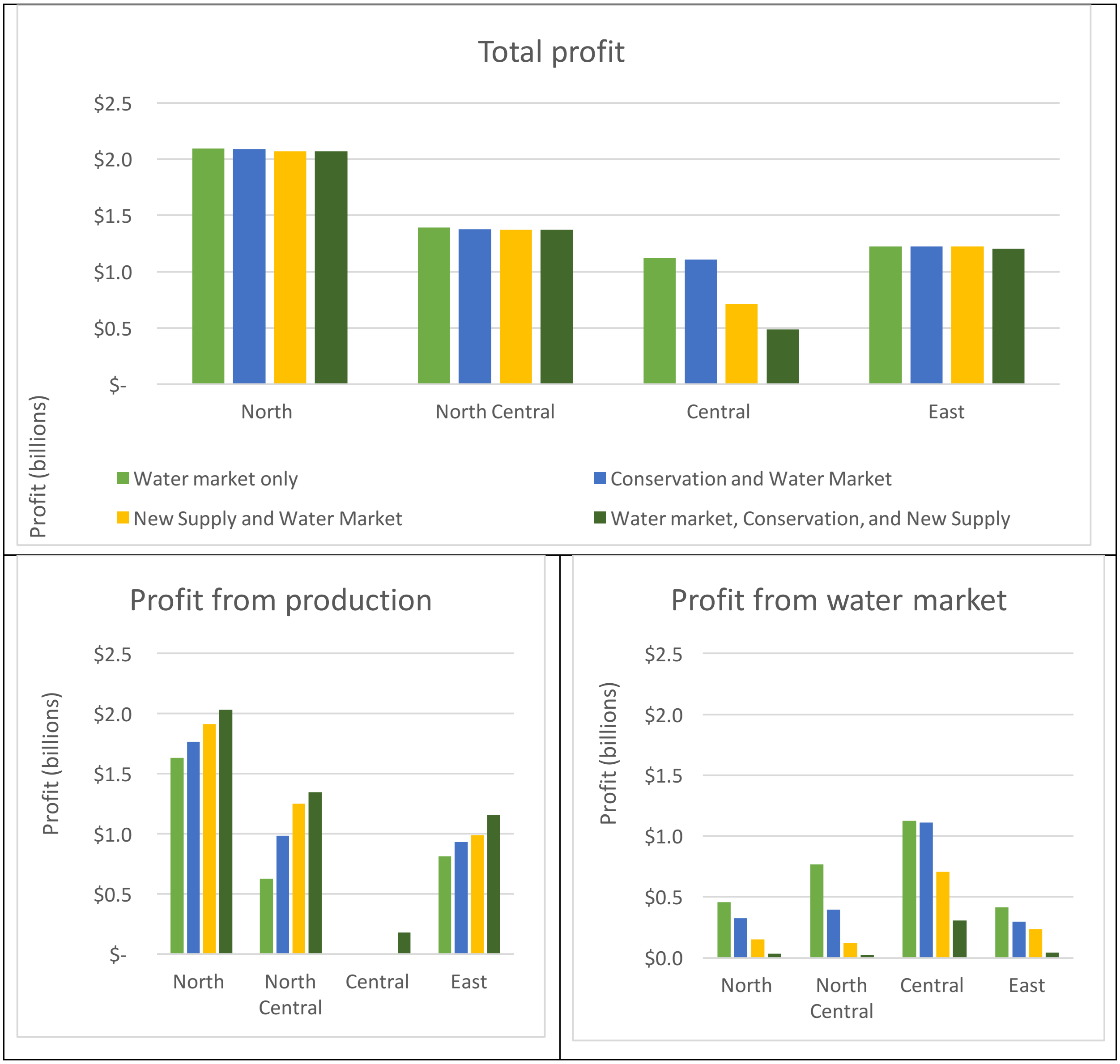

Figure 22. Producer profit by region from production and the water market with and without conservation and new supply, assuming long run population growth and transaction costs

Evaluating the individual components of profit, results show profit from production increases somewhat steadily in North and East as conservation, new supply and both conservation and new supply are introduced. Each strategy leads to less water demanded by M&I firms and thus more water in production. In North Central, the introduction of conservation leads to the largest stepwise increase in profit from production across scenarios of 57%. Central sells all of its water on the market and does not use any in production, with the exception of the last scenario in which a small profit is earned in production.

The introduction of conservation leads to a decrease in profit from the water market in all regions with Central only seeing a very small decrease and North Central seeing the largest decrease. The introduction of new supply leads to a further decrease in profits from the water market for all regions. When all three options are utilized to meet future demand, producer profits from the water market decrease to their lowest level with profits for water poor regions (Central) of $305 million and for water rich regions (North, North Central, and East) ranging from $25 million to 45 million.

What is driving these changes? The price received by the seller and the quantity of water purchased from each region. The price received by the seller and how the price changes with the introduction of conservation and new supply was explored in the previous section and presented in Table 23. The introduction of conservation leads to a very minimal decrease in the regional price of water for all regions except for East, which remains the same. The introduction of new supply leads to no change in the price of water in East, a small decrease in price in North and North Central, and a large decrease in price in Central. When all three means by which to meet future demand are available, the regional price of water is lowest of all scenarios, decreasing for all regions.

With the introduction of conservation, North Central sees the largest decrease in the quantity of water purchased from their region, decreasing by 23,000 acre feet from 48,000 to 25,000 acre feet (Figure 23); explaining the sharp decrease in North Central with the introduction of conservation as the price only sees a very small decrease. The quantity demanded decreases by 7,000 and 5,000 acre feet in North and East, respectively, while Central sees no change in the quantity of water demanded. Water previously sold on the water market is shifted to production, resulting in a very minimal impact of conservation on total profit.

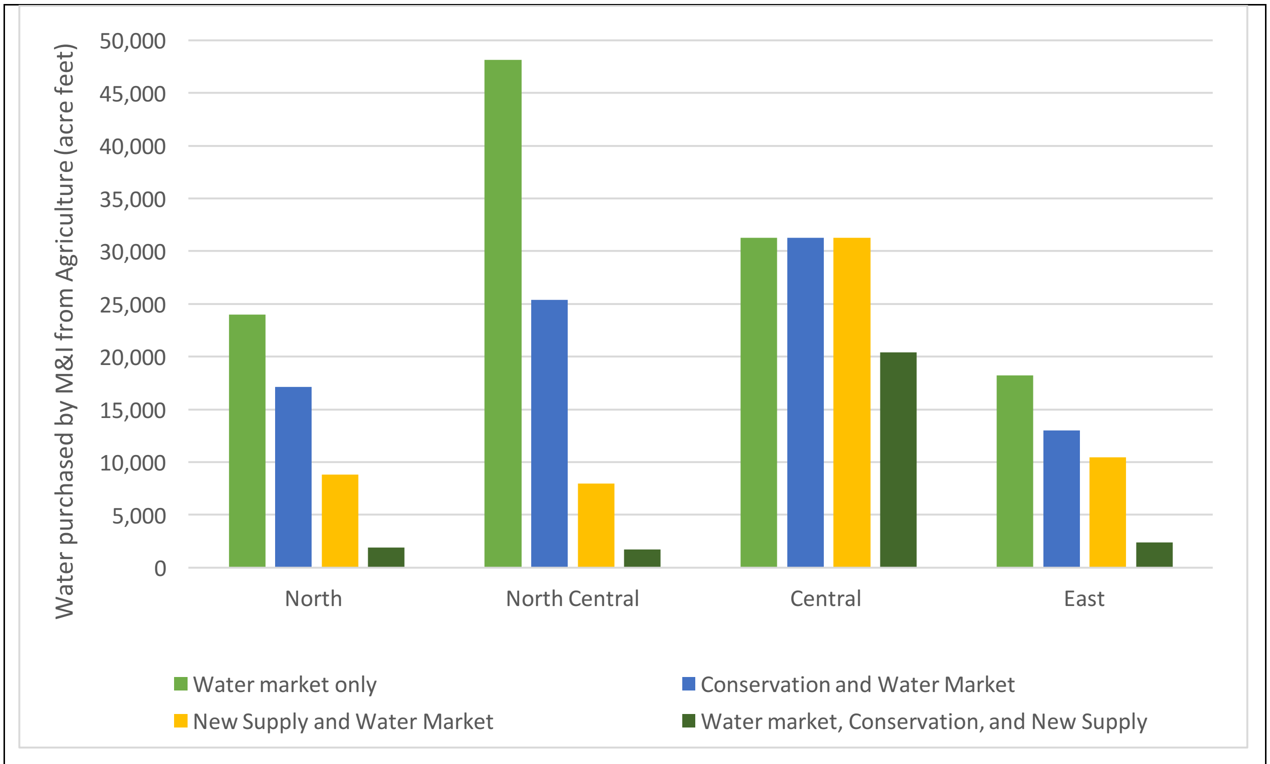

Figure 23. Water purchased by M&I firms from producers in each region (acre feet) with and without conservation and new supply, assuming long run population growth and transaction costs

Results for Central and North Central do not follow the same pattern as the other regions due to the trading that occurs between the two regions. Results are as described by Figure 16 in which interregional trading remains with the introduction of conservation, where North Central is Region 1 and Central is Region 2. Conservation leads to a decrease in market demand, leading to a decrease in the price of water in both regions, a decrease in the quantity demanded in Region 1 and no change in the quantity demanded in Region 2. Both regions see a decrease in producer profit from the water market with the change being larger in the water rich region (Region 1).

The introduction of new supply development leads to a decrease in the quantity of water purchased from all regions with the exception of Central. While the total quantity of water purchased from Central is the same, new supply decreases demand such that Central no longer purchases water from an outside region and has extra water that it sells to East; an important dynamic when it comes to the price of water in Central. The decrease in profit from the water market is a result of a lower price received as well as a smaller quantity being purchased, with the exception of Central in which lower profits are driven solely by a lower price. Water shifts from being sold on the market to being used in production, making up for lost profits on the market for all regions with the exception of Central.

The implications of new supply on the water market dynamic between North Central and Central are the same as those described in Figure 18 in which new supply decreases demand such that interregional trading ceases. Due to decreased demand, M&I firms in Region 2 (Central) no longer purchase water from Region 1 (North Central) nor pay the price of water in Region 1 plus transaction costs. Thus producers in Region 2 (Central) can no longer charge this higher price for water purchased in their own region, largely inflated due to transaction costs, leading to a large decrease in the price of water in Region 2 (Central). The large drop in the price of water leads to a loss in profit from the water market for producers in Central that are not overcome by an increase in profit from production. As both new supply and conservation are introduced, total profits decrease by an even larger amount. The dynamics behind this change are the same as described in the case with only new supply, with a larger decrease in profits resulting from a lower price and quantity of water purchased.

Proponents of alternative supply methods to meet future demand for water, seeking to leave more water in agriculture, claim producers will be better off because more water will remain in agriculture. In the aggregate, alternative supply methods will lead to a very small decrease in the present value of a future stream of total profits earned by most producers in the

South Platte River Basin. Results from this model show that, although producers in some regions receive a lower price for water and sell less water, because more water remains in production, the increase in revenue from production makes up for the majority of the losses. But for the individual producer, the impact of conservation on profits can be significant if that producer chooses to sell all of his or her water rights; this type of producer will not be made better off by conservation and new supply.

3.4.3 Different Levels of Conservation versus Different Levels of New Supply

The impact on producer profits from the interaction between conservation and new supply is evaluated in this section, providing a sensitivity analysis of producer profits under differing levels and combinations of new supply and conservation. Total producer profits are the highest when the water market is the only available option by which to meet future demand (0% of both conservation and new supply) and profits decrease as the percentage of maximum allowable conservation and new supply increase (Figure 24).

For all combinations of conservation and new supply of less than 60%, change in profit is minimal ranging from 0% to 2%, illustrated by the plateau portion of the graphic. But, as larger amounts of new supply and conservation are available as means by which to meet future demand, there is large drop-off in profits, seen by the cliff portion of the graphic.

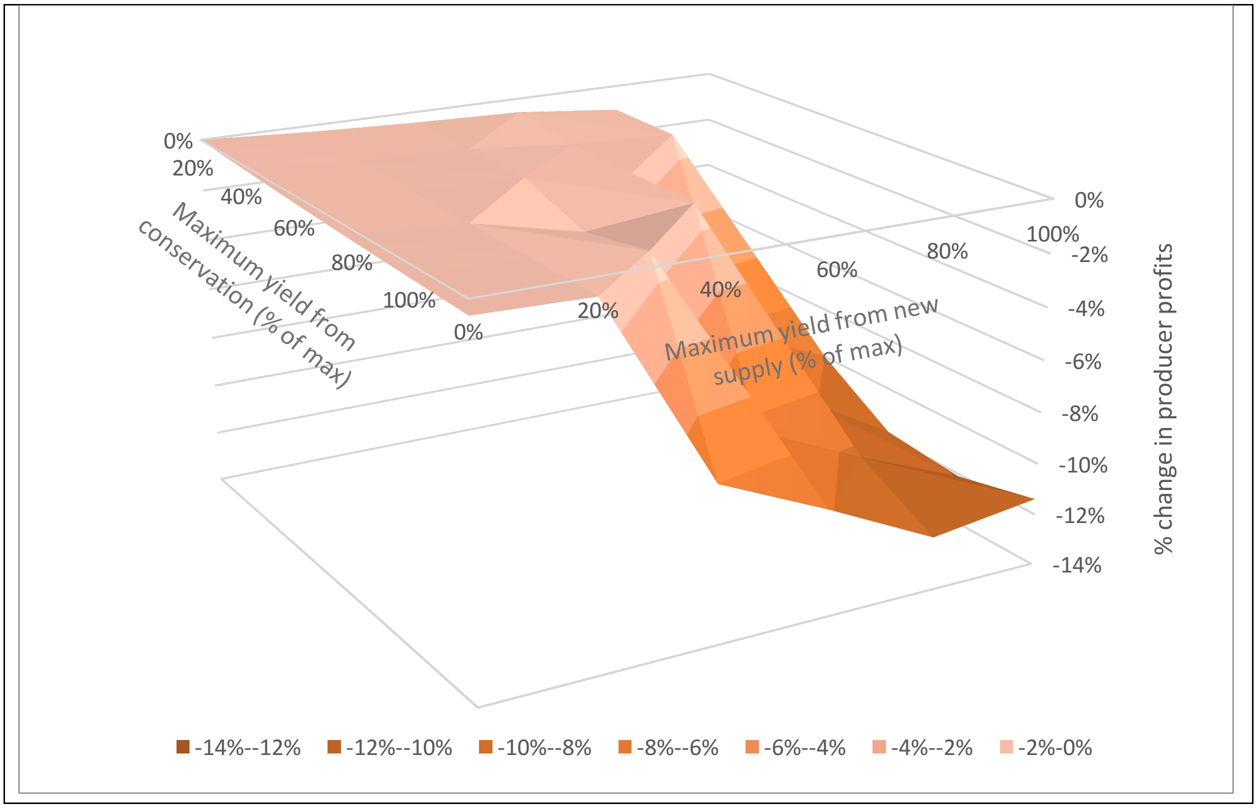

Figure 24. Percent change in producer profits as maximum allowable conservation and new supply increase from 0% to 100% of potential yield compared to 0% of both, assuming long run population growth and transaction costs

The cliff begins at two combinations of conservation and new supply: 80% of maximum conservation and 40% of maximum new supply, and 60% of conservation and 80% of maximum new supply. These combinations are the point at which the demand in the Central region decreases such that it no longer needs to purchase water from an outside region to meet demand, thereby shifting market dynamics significantly and leading to a large decrease in producer profits. Results from this model demonstrate that, at quantities of conservation and new supply below what is projected to be used in the South Platte River Basin to meet future demand, the introduction of both conservation and new supply lead to a sharp decrease in producer profits in the basin.

The driver behind the decrease in producer profits is a decrease in profit from the water market (Figure 25). The same cliff again illustrates that there is a steep drop in producer profits once a certain quantity of conservation and new supply are reached, driven by the same dynamics as described above. Profits from production do not see the same steep change, but rather increase steadily as conservation and new supply increase (Figure 26).

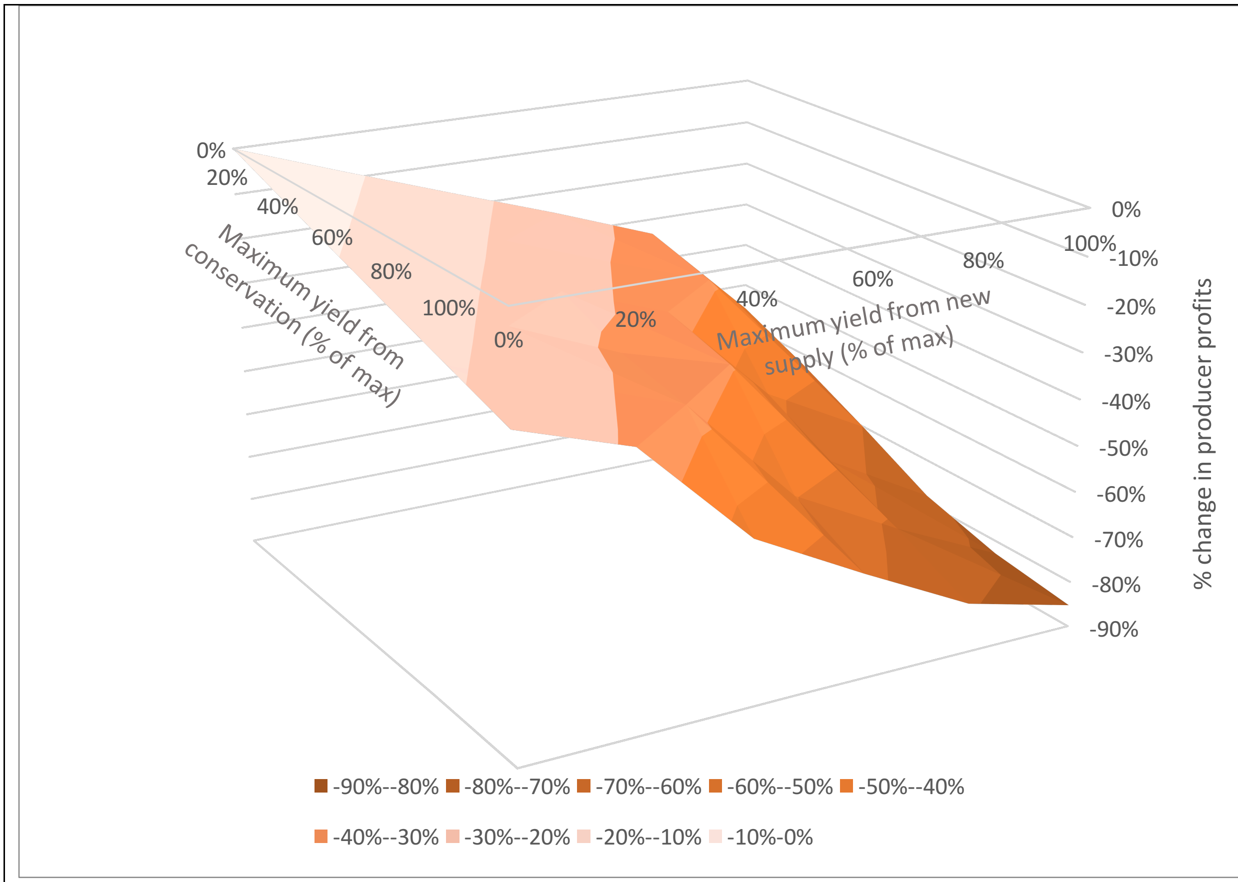

Figure 25. Percent change in producer profits from the water market as maximum allowable conservation and new supply increase from 0% to 100% of potential yield compared to 0% of both, assuming long run population growth and transaction costs

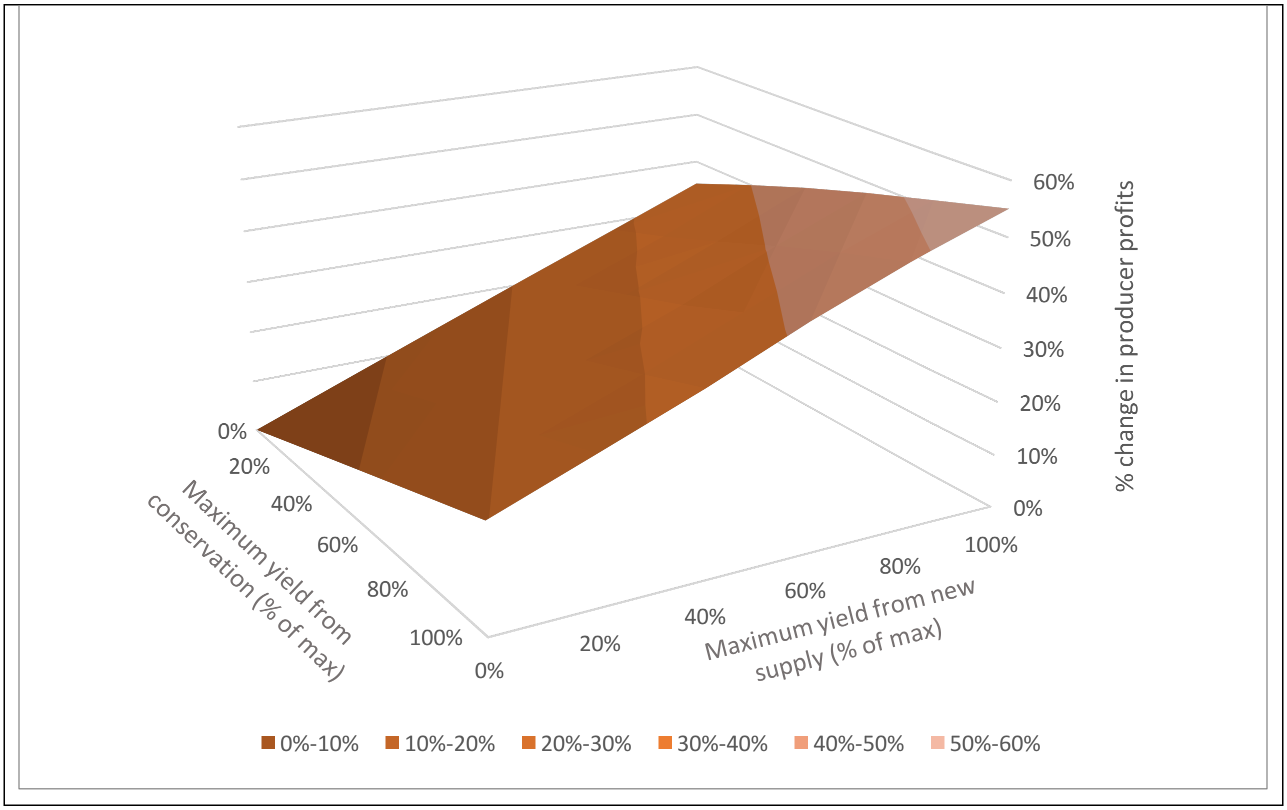

Figure 26. Percent change in producer profits from production as maximum allowable conservation and new supply increase from 0% to 100% of potential yield compared to 0% of both, assuming long run population growth and transaction costs

3.4.4 Regional Economic Impacts

As suggested by proponents of one approach, reducing the reliance on agriculture to supply water for future M&I demand, introducing conservation and new supply increases the amount of water that remains in agriculture and thus increases the revenue generated from agricultural production; whether this increase in revenue leads to an increase in the well-being of rural communities is another question. Bourgeon, Easter, and Smith (2008) find that the impact of a water market on the health of rural economies is largely dependent on whether those who sell their water choose to remain in the region or choose to leave. The revenue generated from agricultural production is only one part of the potential impact of conservation on rural economic activity, the revenue generated from the water market, and whether it is spent in the region or "leaks" to other regions in the form of capital rents, also plays a key role.

The introduction of both conservation and new supply lead to an overall increase in producer revenue, increasing by $580 million with the introduction of conservation, an additional $56 million with the introduction of new supply and an additional $230 million when both new supply and conservation are included (Figure 27). As less water is demanded from M&I as a result of conservation and new supply, less revenue is earned on the water market and more revenue is earned from farm-based production activities.

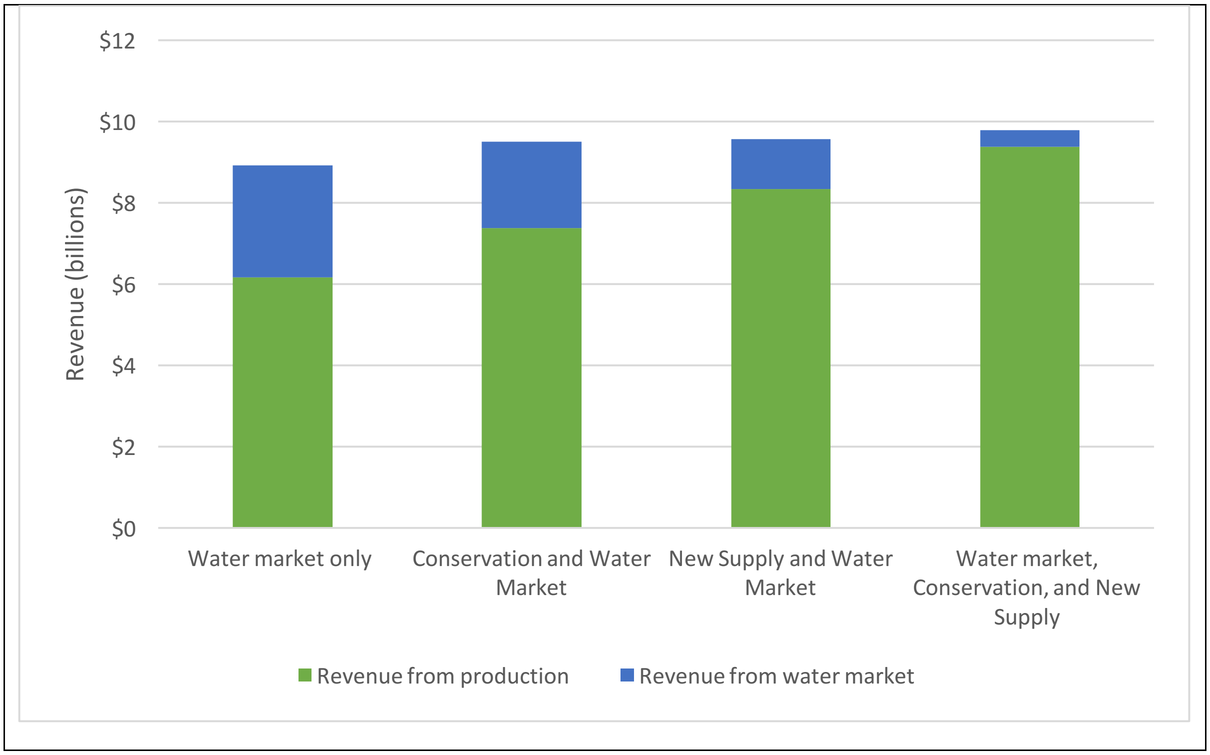

Figure 27. Total producer revenue from production and the water market with and without conservation and new supply, assuming long run population growth and transaction costs

Evaluating the regional changes that drive basin-wide changes, we see that total revenues increase for water rich regions (North, North Central, and East) with the introduction of conservation and new supply while total revenues decrease for water poor regions with high population growth (Central) (Figure 28). All regions see an increase in revenue from production and a decrease in revenue from the water market with the introduction of conservation and new supply. The relative magnitude of these opposing changes drives the differences in the total change in revenue for each region.

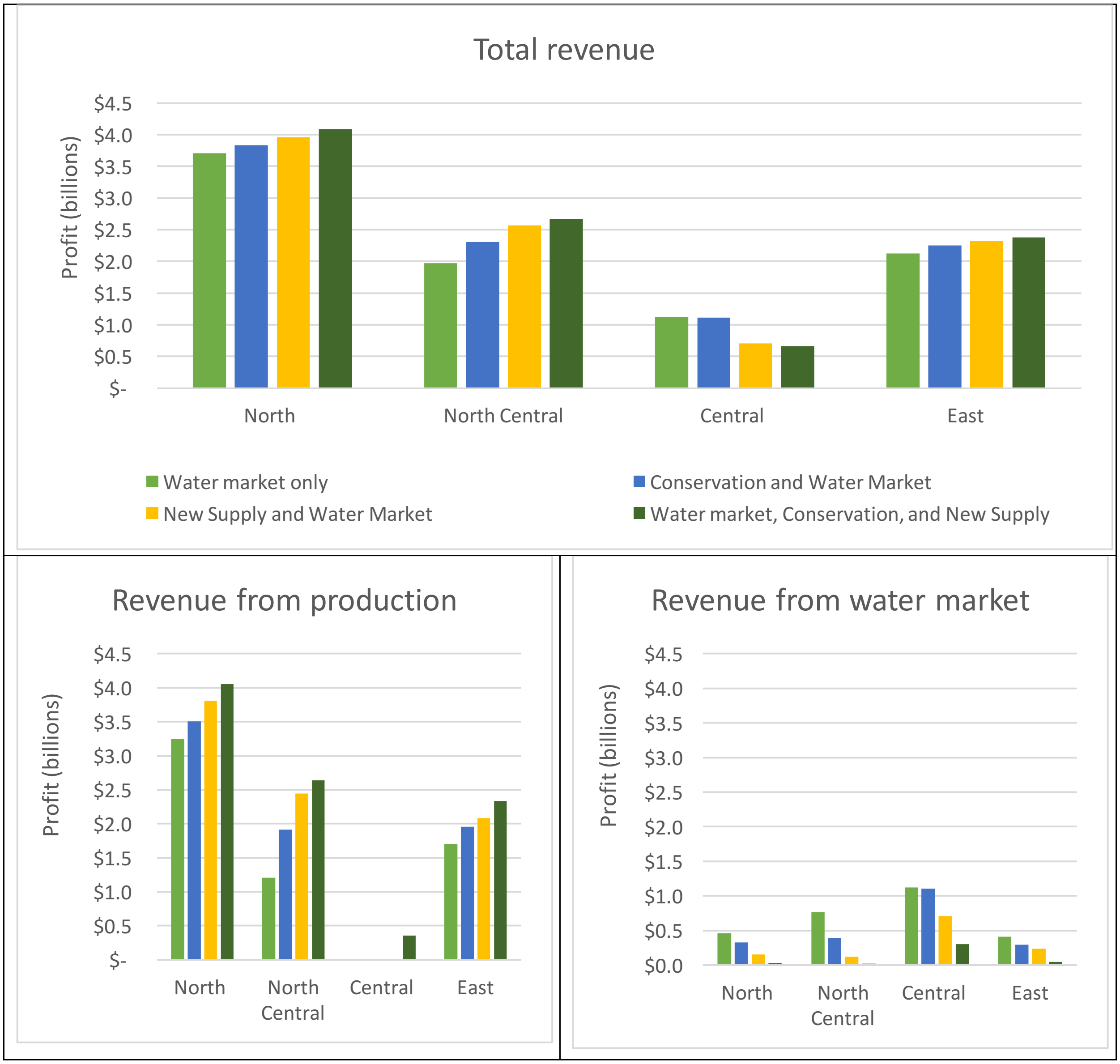

Figure 28. Producer revenue by region from production and the water market with and without conservation and new supply, assuming long run population growth and transaction costs

Next, I expand on the direct economic impact of conservation and new supply resulting from changes in revenue and evaluate what that change means for the economy in each region. To evaluate how the impact of population growth on regional economies will change as conservation and new supply are introduced as means by which to meet future demand, I estimate the change in revenue in one year comparing revenue from a water market only to (1) a water market with conservation, (2) a water market with new supply, and (3) a water market with conservation and new supply. I use the estimated change in revenue to estimate regional economic impacts using the commonly employed input-output model: specifically, the commercially available software IMPLAN (IMpact Analysis for PLANning) from the IMPLAN Group LLC (Minnesota IMPLAN Group, Inc., 2000). Revenue from crop production is calculated simply as the revenue earned from one year of production. Revenue earned on the water market is calculated by taking the present value of the lump sum earned on the water market times, assuming an interest rate of 3% and time period of 50 years, to determine the yearly proceeds generated from the water market.[27]

Following Chapter 2, results for the four changes in revenue are calculated for three different scenarios. The first scenario assumes all money earned from the sale of water rights leaves the region, producers sell their water and leave the region. The second scenario assumes producers remain in the region and spend half of the annual value of proceeds earned from the sale of water rights in their region. The last scenario assumes producers remain in the region and spend the full value of the annual proceeds from the sale of water rights within their region. Scenarios are based off previous research that has found that the impact of a water market on the health of rural economies is largely dependent on whether those who sell their water choose to remain in the region or choose to leave (Bourgeon, Easter, and Smith, 2008).

[27] Note that acres are allocated to each region based on where the water is diverted, which may or may not be the same region in which the acres are located. The regions created in IMPLAN assume the region where water is diverted is the same region where it is used, potentially leading to a small over-estimation of impacts in some regions and underestimation in others. Due to its upstream location, water is diverted in North but used in North Central or other downstream regions. Irrigated acres located in North are higher than in reality, whereas irrigated acres in North Central are lower.

Again, following to Chapter 2, the impact of change in revenue[28] resulting from a change in production is modeled as a decrease in revenue for the agricultural sector[29] and changes in revenue resulting from the sale of water rights are modeled as an increase in household revenue for the median income households in each region[30]. Based on this modeling choice, the economic impact for the agricultural sector remains the same throughout all scenarios as only the portion of money included as household revenue changes with each of the three scenarios.

The first scenario I examine is when it is assumed that producers sell their water rights and leave the region, spending none of the proceeds from the water market locally. Conservation leads to a direct economic impact in the basin of $47.4 million resulting in a total economic impact (direct, plus indirect, plus induced) of $96.3 million, representing 2% of total agricultural output in the basin (Table 25)[31]. The introduction of new supply leads to a larger economic impact with a direct impact for the basin of $84.7 million resulting in a $168.2 million total economic impact, representing 4% of total agricultural output in the basin. The combination of conservation and new supply leads to the largest impact, with a direct impact of $125.4 million leading to a total impact of $248.5 million, representing 6% of total agricultural output.

[28] Change in revenue is used as a proxy for a change in final demand. Although this approach is commonly utilized, it leads to an overestimation of impacts due to double counting.
[29] NAICS sector 11 (Agriculture, Forestry, Fishing and Hunting), with forestry, fishing and hunting removed
[30] Median household income calculated from the American Community Survey (https://www.census.gov/programs-surveys/acs)
[31] Total agricultural output reported for NAICS sector 11 (Agriculture, Forestry, Fishing and Hunting), with forestry, fishing and hunting removed in IMPLAN

Table 25. Economic impact in a single year when conservation and new supply development are introduced into a water market, assuming water sellers leave the region (in millions)

Region	Direct Impact			Total Impact for all Industries (Direct + Indirect + Induced)		
	Conservation	New Supply	Conservation and New Supply	Conservation	New Supply	Conservation and New Supply
North	$10.2	$22.0	$31.3	$15.1	$32.4	$46.2
North Central	$27.4	$48.2	$55.8	$43.9	$77.1	$89.4
Central	$0	$0	$13.7	$0	$0	$21.6
East	$9.8	$14.6	$24.3	$16.3	$24.2	$40.3
Total	**$47.4**	**$84.7**	**$125.4**	**$96.3**	**$168.2**	**$248.5**

North Central sees the largest economic impacts from conservation, new supply and both conservation and new supply with total economic impacts of $43.9 million, $77.1 million and $89.4 million, respectively. Central sees the smallest total economic impacts, ranging from $0 to $21.6 million. When assuming that water market proceeds leave the region, conservation and new supply lead to positive economic impacts for all regions with the exception of Central, which sees no impact with the introduction of conservation and new supply but positive impacts with the introduction of both.

The second scenario I examine is when it is assumed that water rights sellers spend half of their proceeds from water rights sales locally. The increase in revenue from production is partially offset by the decrease in revenue from the water market, resulting in lower economic impacts than in the scenario described above. Total economic impact the basin decreases from $96.3 million to $81.4 million with the introduction of conservation, from $168.2 million to $132.2 million with the introduction of new supply, and from $248.5 million to $193.6 million with the introduction of both conservation and new supply (Table 26). Similar to the previous scenario, North Central sees the largest gains from conservation and new supply, with total economic impacts ranging between $40.2 million and $82.4 million. In this scenario, Central sees a negative economic impact from conservation and from new supply, but positive for the combination, ranging from negative $9.2 million to positive $3.5 million.

Table 26. Economic impact in a single year when conservation and new supply development are introduced into a water market, assuming water sellers spend half of their proceeds from the water market locally (in millions)

Region	**Direct Impact**			**Total Impact for all Industries (Direct + Indirect + Induced)**		
	Conservation	New Supply	Conservation and New Supply	Conservation	New Supply	Conservation and New Supply
North	$7.6	$16.0	$23.1	$12.7	$27.0	$31.2
North Central	$20.1	$35.6	$41.4	$40.2	$71.0	$82.4
Central	-$0.3	-$8.1	-$2.2	-$0.3	-$9.2	$3.5
East	$7.5	$11.1	$17.1	$14.9	$22.2	$36.3
Total	**$35.0**	**$54.7**	**$79.4**	**$81.4**	**$132.2**	**$193.6**

The last scenario I examine is when it is assumed that water rights sellers spend all of their proceeds from water rights sales locally. Results show the smallest economic impacts of all three scenarios evaluated with total economic impacts for the basin resulting from conservation, new supply, and the combination of the two ranging from $81.4 million to $193.6 million (Table 27). A decrease of $30 million to $110 million compared to the first scenario in which it was assumed no proceeds from the water market were spent locally, representing a 31%-44% smaller economic impact.

Table 27. Economic impact in a single year when conservation and new supply development are introduced into a water market, assuming water sellers spend all of their proceeds from the water market locally (in millions)

Region	**Direct Impact**			**Total Impact for all Industries (Direct + Indirect + Induced)**		
	Conservation	New Supply	Conservation and New Supply	Conservation	New Supply	Conservation and New Supply
North	$5.1	$10.1	$14.8	$10.4	$21.6	$38.7
North Central	$12.9	$23.0	$26.9	$36.8	$64.9	$75.3
Central	-$0.5	-$16.1	-$18.1	-$0.6	-$18.3	-$14.6
East	$5.2	$7.7	$9.9	$13.6	$20.3	$32.2
Total	**$22.5**	**$24.7**	**$33.6**	**$66.5**	**$96.2**	**$138.7**

Overall, conservation and new supply lead to a positive regional economic impacts, but for water scarce regions with high population growth conservation can have negative economic impacts. The magnitude of economic impacts impacts decreases as a higher proportion of proceeds from the water market are assumed to be spent locally. The positive economic impacts resulting from increased revenue from production are partially offset by the negative economic impacts from decreased revenue from the water market.

3.5 Conclusion

In the western U.S., long run demand for water will be met through a variety of means including water transfers from agriculture to municipalities, conservation and building new supply. Advocates of utilizing a portfolio approach to meeting future demand for water claim that it will lead to lower costs for municipalities to meet future demand and increased well-being of rural areas as more water will remain in agriculture. Results from this paper demonstrate that introducing conservation and new supply as a means by which to meet long run demand for water, in addition to purchasing water on the market, leads to a decrease in the average cost per capita across the basin to meet long run demand for water. Differences across regions demonstrate that water scarce regions with high population growth see the largest reductions in the cost to acquire water as a result of conservation and new supply.

In the South Platte River Basin, compared to the case with the water market only, introducing conservation leads to a decrease in the average cost per acre foot to acquire water in order to meet long run population growth of around 17%. Introducing new supply development, compared to the water market only, leads to an average decrease of 34% in the cost to acquire water and utilizing all three means by which to meet future demand leads to the largest reduction in the average cost to acquire water, with costs basin-wide decreasing by 57%. The portfolio approach to acquiring water to meet future demands results in fewer transactions taking place on the water market resulting in a diversification of costs spent to acquire water.

The introduction of conservation does not lead to a change in the price of water received by the seller. Driven by the small variance of the marginal value of an acre foot of water in production and the fact that conservation does not change transaction costs incurred, leading to small average decrease in the cost to acquire water on the market. The introduction of new supply, on the other hand, does cause a decrease in the price of water for most regions, with the largest decrease in price seen in water poor regions with high population growth and access to water from within their own region, driven largely by transaction costs. As M&I demand for water decreases such that firms no longer have to purchase water from an outside region, market dynamics can shift significantly, largely due to large transaction costs no longer being incurred by the M&I firms.

Total producer profits in all regions, with the exception of producers in water poor regions with high population growth, remain virtually unchanged as conservation, new supply and both conservation and new supply are introduced into a water market. As less water is demanded by M&I firms, producer profits shift from being earned on the water market to being earned from production. The increase in profits from production offsets the decrease in profits from the water market in all regions with the exception of water poor regions with high population growth.

Proponents of the portfolio approach to meeting future demand for water claim producers will be better off because more water will remain in agriculture. In the aggregate, conservation and new supply will lead to a very small decrease in the present value of a future stream of total profits earned by most producers in the South Platte River Basin. Results from this model show that, although producers in some regions receive a lower price for water and sell less water, because more water remains in production, the increase in revenue from production makes up for the majority of the losses. But for the individual producer, the impact of the portfolio approach on profits can be significant if that producer chooses to sell all of his or her water rights; this type of producer will not be made better off by conservation and new supply. A decrease in the price of a water right will mean less profits received from their sale.

Overall, conservation and new supply lead to a positive regional economic impacts, but for water scarce regions with high population growth conservation can have small negative economic impacts. The magnitude of economic impacts decreases as a higher proportion of proceeds from the water market are assumed to be spent locally. The positive economic impacts resulting from increased revenue from production are partially offset by the negative economic impacts from decreased revenue from the water market.

Chapter 4: Conclusion

Due to increases in population and continued migration to many Western US states, a gap between water demand for municipal and industrial (M&I) use and available water supplies is forecasted. Increased demand for water will likely be addressed using a combination or portfolio of three approaches: voluntary water transfers (typically from agriculture to municipal users), water conservation, and developing new supplies/expanding existing supplies. This dissertation explores impacts to M&I users, agricultural producers, and rural communities considering the different considerations that may influence how that portfolio of approaches is balanced and by which future demand will be met.

To more realistically frame relevant factors underlying the portfolio of water market management choices, I model multiple, integrated, regional water markets consisting of firms that are heterogeneous, both in terms of objectives and situation. Producers are assumed to maximize expected profit; whereas the goal of M&I firms is to minimize the cost of acquiring enough water rights to meet forecasted demand. Heterogeneous transaction costs are included in the model and incurred when purchasing water. Although transaction costs have been included in previous water market models as a constant marginal cost (e.g., Howitt et al., 2012; Zhu et al., 2015), the novel way in which I include transaction costs is a key contribution. A more accurate representation of net returns and spatial variance is integrated by allowing for regional "pools" of water (e.g., ditch company) where firms face institutional transaction costs (assumed to be constant across regions) when trading within a pool, but face both institutional and physical transaction costs (assumed to vary based on the location of the buyer and seller) when trading across pools.

The model presented in this dissertation contributes to the optimization modeling literature by providing a modeling framework that allows the inclusion of firms with differing objective functions and heterogeneous transaction costs, solved using an individual maximization framework. While this model is presented in the context of water, it could be used in a variety of other situations where there are important spatial dimensions that may influence the relative costs of transactions due to physical distance, regulatory regimes and other costs of policy or institutional factors. Example of other fields of study where such heterogeneity in factors may be important in understanding reallocation and management decisions include land conservation, fisheries, energy and some product trade.

Results demonstrate that heterogeneous transaction costs play a large role in the welfare outcomes resulting from a water market, and in particular, demonstrate how those outcome differ across regions. Results from the South Platte River Basin show that producers who own water rights earn positive profits in the face of population growth because they are able to sell their water rights on the water market (confirming previous research), but those gains vary greatly across users based on their location (and effective net returns) as costs vary within the basin.

In an effort to better understand how transaction costs impact producer and consumer welfare, I find some results that may run against conventional wisdom. Specifically, reducing transaction costs reduces the increase in total producer profits resulting from population growth, making some producers worse off. Moreover, the change in profits resulting from a decrease in transaction costs varies widely by region where those producers located in water scarce regions see the largest decrease in profits, illustrating the importance of allowing for spatial heterogeneity.

For consumers, on the other hand, reducing transaction costs leads to a lower price for municipal water, theoretically making households better off due to a lower cost of water. As was the case with producers, savings vary across regions. Consumers located in water scarce regions with high population growth see the largest reduction in prices when transaction costs are reduced, perhaps allowing for market signals to run counter to the signals conservation leaders would hope to encourage water-saving behavior.

Results show the importance of including heterogeneous transaction costs in a water market model as these costs have significant impacts on model outcomes. Most importantly, results demonstrate the heterogeneity in impacts across both regions and firm type, lending credence to the modeling framework developed in this dissertation.

Limitations and Future Research

To simplify this model and to provide a basic framework to analyze market impacts of transaction costs, numerous simplifying assumptions were made. I hope to relax some of these assumptions in the future to enable a more detailed policy analysis from this model. The first assumption I make is that crop prices in the long run will be the same as an average of the past 5 years. As history has shown, crop prices fluctuate significantly, and thus, are unlikely to stay the same in the future. A shift in crop prices and/or input costs could significantly alter model outcomes. Although predicting long run crop prices and input costs is beyond the scope of this modelling, one option for future analysis would be to run a sensitivity analysis on all of the parameters in the model. This exercise would show how dependent results are on specific parameter estimates, providing a range of estimates.

The second assumption that I make is that climate conditions be the same in the future as they have been in the past, both in terms of water availability and crop water use. This is unlikely to be the case as a result of climate change and is an area for future model simulations. The data presented in this model is on a relatively large scale, where both firms and transaction costs are presented on a regional level. In future modeling efforts, I would like to reduce this scale to the ditch level to get a more detailed account of how water will move throughout the basin. The third assumption that I make is in regards to the relative price of water to M&I firms and to producers. There is currently a wedge between the price of water on the market and the value of water in agriculture. This wedge is, in part, a result of producer speculation regarding the future price of water. I assume this wedge remains constant over time. In reality, it is possible that this wedge could either increase or decrease as prices, transaction costs, or both change, and is another area for sensitivity analysis.

The fourth assumption I make is in regards to how producers make decisions over time and the time value of money. To compare profits earned on the water market, a lump sum payment, derived from profits earned from production was estimated assuming a 50-year time horizon and 3% interest rate. The expectation of prices both in terms of production and water over time is likely to influence producer decision making and is not included in the model. A future iteration of the model could include a more detailed analysis of producer expectations and how those expectations influence model results.

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