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Modeling Imperfectly Competitive Water Markets in the Western U.S.

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Abstract

Water is an essential ingredient to growing communities, healthy ecosystems and vibrant industries. Due to increases in population in the western U.S., the gap between forecasted water demands and available water supplies is growing. One of the primary means by which increased demand for water will be met is through voluntary water transfers. 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. In this paper, we explore the function of water markets when perfectly competitive conditions do not exist, answering the question, how does the presence of transaction costs in water markets impact welfare outcomes, in terms of overall efficiency and distributional impacts? As a secondary research question, this paper explores how different buyers and sellers are differentially affected by transaction costs, and thus, any policy measures to reduce such costs. Results from this paper show that heterogeneous agents and the existence of transaction costs do play a role in welfare outcomes from the water market, showing the importance of modeling imperfectly competitive water market to provide more nuanced policy and market analysis.

Key words: transaction costs, water market, imperfect competition

Introduction

Water is an essential ingredient to growing communities, healthy ecosystems and vibrant industries. Due to increases in population in the western U.S., the gap between forecasted water demands and available water supplies is growing. For example, the population in Colorado is projected to nearly double by 2050 requiring an additional one million acre/feet of water per year, yet unappropriated water (or water that is not currently being put to beneficial use) in Colorado is extremely limited (Statewide Water Supply Initiative, 2010).

Increased demand for water will be met by a combination of three means: voluntary water transfers (typically from agriculture to municipal users), water conservation, and developing new supplies. 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). Government agencies have also promoted water markets; the Western Governors Association is currently investing significant resources in examining the best means for facilitating transfers (Iseman, et al., 2012), and Colorado is assuming 70% of the 2050 municipal and industrial water demand will be met by voluntary transfers from agriculture (Statewide Water Supply Initiative, 2010). In this paper, I will explore the function of water markets when perfectly competitive conditions do not exist, answering the question, how does the presence of transaction costs in water markets impact welfare outcomes, in terms of overall efficiency and distributional impacts?

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 have been used extensively to examine water markets (Harou, et al., 2009 survey many approaches, current examples include Wang, Fang, & Hippel, 2008; Gohar & Ward, 2010 and Howitt, et al., 2012; Jiang & Grafton, 2012). A common feature of hydro-economic models is the assumption of a perfectly competitive market structure, and as a result, use a single objective function that maximizes net benefits. This structure does not allow authors to consider several real world phenomena, including heterogeneous agents. Ignoring these phenomena means the models may have difficulty in describing the efficiency and distributional equity of market transactions.

A single objective function assumes that all water users make decisions based on the welfare of all water users in the basin; in reality, water users make decisions based on their individual welfare. Additionally, the single objective function forces a producer and a municipality to have the same objective, often to maximize net benefit. A producer maximizes profit while in the municipal water use sector, water supply is typically chosen so as to minimize the risk of a shortfall rather than to maximize net benefit (Griffin & Mjelde, 2000; Timmins, 2003). If a municipality is modeled in the typical benefit maximization framework, we would assume the municipality minimizes the cost of acquiring water subject to an optimal level of consumer utility[1] rather than subject to a minimum water supply level. The latter typically leads to purchasing a larger amount of water than the former.

I model individual water user optimization functions in which municipal and industrial water users have a different objective function than producers. Although individual optimization in has recently been utilized in water market models (Kuhn & Britz, 2012; Britz, Ferris, & Kuhn, 2013), my work builds on the previous individual optimization models by including different

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

objective functions based on user type, leading to different welfare outcomes due to a more accurate characterization of agent behavior.

Perfect competition assumes a large number of buyers and sellers, no barriers to entry or exit, profit maximization, 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 few buyers and many sellers, imperfect information, non-profit maximizing behavior, heterogeneous goods, and relatively large transaction costs persist in many basins (Colby, 1990; Timmins, 2002; Howe & Goemans, 2003; Iseman, et al., 2012). This paper will relax the assumption of perfectly competitive market conditions by assuming the existence of increasing returns to scale, transaction costs, non-profit maximizing behavior, and treating water as a heterogeneous good.

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), as 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). This paper will focus on legal transaction costs associated with the water market rather than the physical transaction costs. Transactions costs have been one of the more discussed aspects of water markets publically and in the literature and yet they have been rarely accounted for in water market models.

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 (e.g. Howitt et al., 2012), the novel way in which I include them are twofold: one, I allow for regional "pools" of water where there is perfect competition within a pool, but imperfect competition across pools (due to transactions costs) and two, I explore varying transaction costs based on location rather than representing them as a constant marginal cost that is the same across all transactions.

In contrast to previous studies, I relax the assumptions of perfect competition by assuming (1) not all agents have objectives that are consistent with the traditional profit/utility maximizing goals, (2) transactions costs exist (including economies of scale in trading the market commodity), and (3) heterogeneity exists in the market commodity being traded. The latter comes in the form of regional pools of water markets.

My specific research question is: how does the presence of imperfectly competitive conditions in water markets impact welfare outcomes, in terms of overall efficiency and distributional impacts? This research questions will be answered by:

a) Developing an individual optimization framework that results in a measure of economic welfare for heterogeneous producer agents in which water is a primary factor of production and heterogonous municipal and industrial agents, where water is traded in an imperfectly competitive market.
b) Adapting the model to a specific case study of the South Platte River Basin in Colorado and analyzing changes in welfare outcomes and important endogenous variables as transaction costs are reduced.

Analytical Framework

The algebraic description will begin with a simple model that can be easily manipulated by hand in order to demonstrate the features of the model. In the simple model, there is one output, one region, and one time period. These simplifications will be relaxed in the final model that will be used in the analysis. I begin with the simple baseline model that represents the baseline scenario that is used as a means of comparison.

In this model there are two types of agents: producer and municipal and industrial (M&I). Producer agents produce one output by choosing the amount of water and land to use in production as well as the amount of water to buy or sell on the water market so as to maximize profit. Water use is constrained by their current endowment of water (i.e. water right amount) but can be augmented by the water market. M&I agents choose to buy water today to meet forecasted demand for water with the objective of minimizing the cost of buying water[2]. M&I agents start with an endowment of water and buy additional water up to the point where future demand for water is satisfied. This is contrary to previous hydro-economic models with both producer and M&I agents, in which M&I agents maximize a net benefit function derived from consumer demand for water. My approach more accurately represents the fact that M&I agents acquire water so as to minimize the risk of a shortage rather than based on the prices their customers are willing to pay for water.

In the water market of this paper, producer agents can buy from other producer agents, sell to other producer agents, or sell to M&I agents. M&I agents can only buy from producer agents. Water is sold into a regional pool and purchased from a regional pool, rather than traded

[2] Buying water takes time, often decades. M&I buyers use projections for future water demand as a basis for the amount of water they need to purchase in the current time period.

directly between agents. The market clearing price is determined by the total amount of water bought and sold in the regional pool.

The equilibrium is defined by the level of output, price of output, quantity of water traded, and price of water that results when producers seek to maximize their profits by choosing the water to use in production, the amount of water to buy/sell, and land allocation while at the same time M&I seeks to minimize the costs of meeting future demand for water. Agents optimize according to their own idiosyncratic production/cost functions. The welfare for the agents will be measured as the profit for the producer (based on output price, output quantity, price of water, and the quantity of water traded), and total cost to the water provider for M&I agents (based on price of water and quantity of water traded). In an equilibrium, the amount of water that is purchased by all agents is no greater than the amount sold.

After the simple model and implications of the first order conditions are discussed, I modify agent interactions on the market by adding transaction costs. Transaction costs are characterized as function of the quantity of water purchased and thus vary across users, due to the differing marginal productivity across users. Outcomes of the baseline model are compared to the model with transaction costs and the welfare impact of transaction costs is discussed. The key variables by which welfare outcomes will be evaluated are changes in producer profit (producer welfare) and changes in M&I cost of acquiring water (consumer welfare). Lastly, the model is expanded by indexing choice variables by output type, time, and region so as to more accurately reflect the complexity of a river basin and enable to the analysis to evaluate welfare outcomes of various climate change and population change scenarios. The last model presented will be the utilized in the remainder of the paper to explore alternative scenarios.

Simple Baseline Model

Producer Profit Maximization Problem

The simple version of the baseline profit maximization problem for the producer with two inputs and one output is as follows:

$$\max_{w,l,s,b} \pi_i = P_y F(w_i, l_i) - c_w w_i - c_l l_i + P_w s_i - P_w b_i \tag{1}$$

where $P_y =$ output price per unit, $F(\cdot) =$ is a production function describing output where $F(w,l) = f(w) \cdot l$, $w_i =$ water use by agent *i*, $l_i =$ land use by agent *i*, $c_w =$ cost per unit of using water in production, $c_l =$ cost per unit of using land in production, $P_w =$ price per unit of water, $s_i =$ the amount of water sold by agent *i* into the regional pool, $b_i =$ the amount of water bought by agent *i* from the regional pool. I assume the technology set is convex, monotonic, closed, bounded, and non-empty (e.g. $F'(\cdot) \geq 0, F''(\cdot) \leq 0$). Output price, the production function, and cost of water and land are exogenous. Water use, land use, price of water, and the quantity of water bought and sold on the market are endogenously determined.

The agent is subject to the following constraints:

$$\begin{aligned} & w_i \geq 0 \\ & l_i \geq 0 \\ & s_i \geq 0 \\ & b_i \geq 0 \\ & w_i + s_i \leq \overline{w}_i + b_i \\ & l_i \leq \overline{l}_i \end{aligned} \tag{2}$$

where $\overline{w}_i =$ initial endowment of water for agent *i* and $\overline{l}_i =$ initial endowment of land for agent *i*. The first four constraints ensure non-negative input use or water transfers. The fifth constraint constrains water use by ensuring the 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 agent 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 agent. The resulting Lagrangian is as follows:

$$L_i = P_y F(w_i, l_i) - c_w w_i - c_l l_i + P_w s_i - P_w b_i + \lambda_i(\overline{w}_i + b_i - s_i - w_i) + \delta_i(\overline{l}_i - l_i) \tag{3}$$

where λ_i is the value of relaxing the constraint on water use by one unit and δ_i is the value of relaxing the constraint on land use by one unit. Both represent the agent's willingness to pay for an additional unit of water and land, respectively.

The solutions to this problem are $w_i^*, l_i^*, s_i^*, b_i^*, \lambda_i^*,$ and δ_i^* and satisfy the following first order conditions:

$$\frac{\partial L_i}{\partial w_i} = P_y F_w(w_i, l_i) - c_w - \lambda_i \leq 0 \qquad \text{c.s. } w_i \geq 0 \tag{4}$$

$$\frac{\partial L_i}{\partial l_i} = P_y F_l(w_i, l_i) - c_l - \delta_i \leq 0 \qquad \text{c.s. } l_i \geq 0 \tag{5}$$

$$\frac{\partial L_i}{\partial s_i} = P_w - \lambda_i \leq 0 \qquad \text{c.s. } s_i \geq 0 \tag{6}$$

$$\frac{\partial L_i}{\partial b_i} = -P_w + \lambda_i \leq 0 \qquad \text{c.s. } b_i \geq 0 \tag{7}$$

$$\frac{\partial L_i}{\partial \lambda_i} = \overline{w}_i + b_i - s_i - w_i \geq 0 \qquad \text{c.s. } \lambda_i \geq 0 \tag{8}$$

$$\frac{\partial L_i}{\partial \delta_i} = \overline{l}_i - l_i \geq 0 \qquad \text{c.s. } \delta_i \geq 0 \tag{9}$$

I will consider two cases, the first assumes a positive amount of water is transferred by agent *i*, this includes buying and selling, and the second assumes no water is bought or sold by agent *i*. It is assumed that a positive amount of water is used in production in both cases. First, I consider the case when water is transferred on the water market, either $s_i^* > 0$ or $b_i^* > 0$. Then it must be the case the following equations hold:

$$
\begin{aligned}
&P_y F_w(w_i, l_i) - c_w = \lambda_i \\
&P_w = \lambda_i \\
&\Rightarrow P_y F_w(w_i, l_i) - c_w = P_w
\end{aligned} \tag{10}
$$

Agent *i* will use water in production up to the point where the marginal value of water used in production equals the price of water on the water market. Remaining water will be exchanged on the market. In the second case, no water is transferred, $s_i^* = b_i^* = 0$. If the agent chooses not to buy water, $b_i^* = 0$ and the following must hold:

$$
\begin{aligned}
&P_y F_w(w_i, l_i) - c_w = \lambda_i \\
&\lambda_i < P_w \\
&P_y F_w(w_i, l_i) - c_w < P_w
\end{aligned} \tag{11}
$$

The marginal profit from crop production is less than the price of water on the water market. Buying water on the market would make the producer worse off than using their water in production.

If the agent chooses not to sell $s_i^* = 0$ and the following must hold:

$$
\begin{aligned}
&P_y F_w(w_i, l_i) - c_w = \lambda_i \\
&\lambda_i > P_w \\
&P_y F_w(w_i, l_i) - c_w > P_w
\end{aligned} \tag{12}
$$

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 agent chooses not to buy or sell water on the market because they will always be better off using their current water endowment in production and not participating in the water market.

Municipal and Industrial Cost Minimization Problem

The simple version of the baseline cost minimization problem for M&I is as follows:

$$
\min_b C_i = P_w b_i \tag{13}
$$

where the agent seeks to minimize the cost of acquiring water subject to the following constraints:

$$\begin{aligned} & b_i \geq 0 \\ & \text{baseline demand}_i \leq \bar{w}_i + b_i \end{aligned} \tag{14}$$

where $\text{baseline demand}_i =$ the projected demand for water for agent *i* given current water use and population projections. This results in the following Lagrangian:

$$L_i = P_w b_i + \lambda_i (\bar{w}_i + b_i - \text{baseline demand}_i) \tag{15}$$

The solutions to this problem are b_i^* and λ_i^* and satisfy the following first order conditions:

$$\frac{\partial L_i}{\partial b_i} = P_w + \lambda_i \geq 0 \qquad \text{c.s. } \mathrm{b}_i \geq 0 \tag{16}$$

$$\frac{\partial L_i}{\partial \lambda_i} = \bar{w}_i + b_i - \text{baseline demand}_i \geq 0 \qquad \text{c.s. } \lambda_i \geq 0 \tag{17}$$

When an M&I agent chooses to buy water, $\mathrm{b}_i^* > 0$ and $P_w = -\lambda_i$. The agent will buy water up to the point where the cost of an additional unit of water to meet baseline demand is equal to the price of water. Assuming the constraint is binding, the total amount of water purchased by the agent can be calculated as $b_i = \text{baseline demand}_i - \bar{w}_i$.

Market Equilibrium

The market equilibrium price for the regional pool is defined by following condition:

$$\sum_i b_i = \sum_i s_i \tag{18}$$

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 agents in the water market determine the market clearing price of water.

Simple Model with Transaction Costs

Producer Profit Maximization Problem

Now that the simple model has been identified, transaction costs will be added; I assume the buyer pays the transaction cost. The producer model with transaction costs is as follows:

$$\max_{w,l,s,b} \pi_i = P_y F(w_i, l_i) - c_w w_i - c_l l_i + P_w s_i - P_w b_i + tc(b_i) \tag{19}$$

where $tc(b_i) =$ transaction cost as a function of total water bought that is incurred by buyer from transferring water on the water market. The constraints are the same as previously stated, resulting in the following Lagrangian:

$$L_i = P_y F(w_i, l_i) - c_w w_i - c_l l_i + P_w s_i - P_w b_i + tc(b_i) + \lambda_i(\bar{w}_i + b_i - s_i - w_i) + \delta_i(\bar{l}_i - l_i)$$

The solutions to this problem are $\tilde{w}_i, \tilde{l}_i, \tilde{s}_i, \tilde{b}_i, \tilde{\lambda}_i,$ and $\tilde{\delta}_i$ and satisfy the following first order conditions:

$$\frac{\partial L_i}{\partial w_i} = P_y F_w(w_i, l_i) - c_w - \lambda_i \le 0 \qquad \text{c.s. } w_i \ge 0 \tag{20}$$

$$\frac{\partial L_i}{\partial l_i} = P_y F_l(w_i, l_i) - c_l - \delta_i \le 0 \qquad \text{c.s. } l_i \ge 0 \tag{21}$$

$$\frac{\partial L_i}{\partial s_i} = P_w - \lambda_i \le 0 \qquad \text{c.s. } s_i \ge 0 \tag{22}$$

$$\frac{\partial L_i}{\partial b_i} = -P_w - tc_b(b_i) + \lambda_i \le 0 \qquad \text{c.s. } b_i \ge 0 \tag{23}$$

$$\frac{\partial L_i}{\partial \lambda_i} = \bar{w}_i + b_i - s_i - w_i \ge 0 \qquad \text{c.s. } \lambda_i \ge 0 \tag{24}$$

$$\frac{\partial L_i}{\partial \delta_i} = \bar{l}_i - l_i \ge 0 \qquad \text{c.s. } \delta_i \ge 0 \tag{25}$$

Once again it is assumed that a positive amount of water is used in production, but I now consider a few different scenarios for the water market. First consider the case when agent *i* is a high value ag producer and we assume a buyer on the water market, $\tilde{b}_i > 0$ and $\tilde{s}_i = 0$. The cost of

acquiring water in the market is less than the benefit from applying the purchased water in production, so the trader buys until the cost of the last increment of water equals the benefit from its use and the following equations hold:

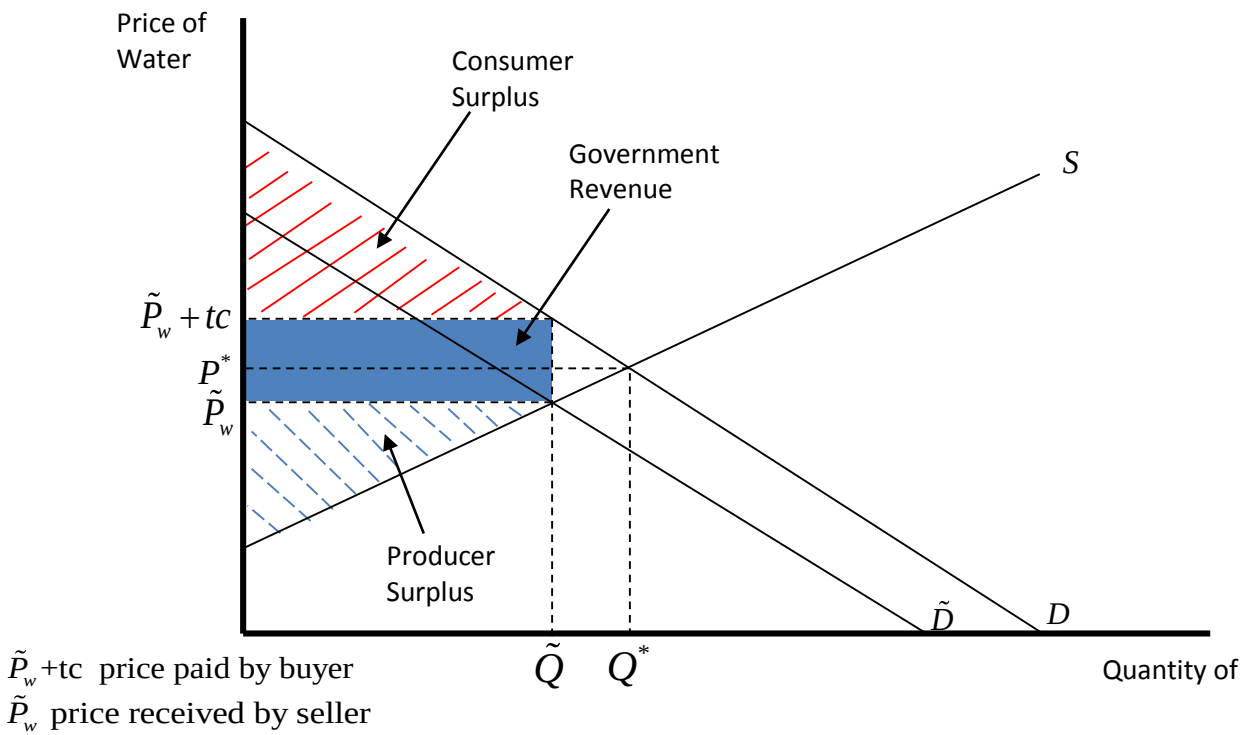
$$\begin{aligned} &P_y F_w(w_i, l_i) - c_w = \lambda_i \\ &P_w + tc_b(b_i) = \lambda_i \\ &\Rightarrow P_y F_w(w_i, l_i) - c_w = P_w + tc \end{aligned} \tag{26}$$

Agent *i* will use water in production up to the point where the marginal value of water used in production equals the price of water on the water market plus transaction costs; in this case, transaction costs act similar to a tax. Comparing the market with transaction costs to our baseline scenario we see:

$$\begin{aligned} &P_y F_w(w_i^*, l_i^*) - c_w = P_w^* + tc_b(b_i^*) > \tilde{P}_w = P_y F_w(\tilde{w}_i, \tilde{l}_i) - c_w \\ &\Rightarrow \tilde{w}_i < w_i^* \end{aligned} \tag{27}$$

Compared to the case without transaction costs, when the agent has to pay a higher price for water, $\tilde{P}_w + tc_b(b_i) > P_w^*$, they buy less water and therefore have less water for production and the seller receives a lower price for water. Figure one depicts the impact of transaction costs on market supply and demand, equilibrium price and quantity. The burden of the transaction cost paid by the buyer and seller depend on the relative elasticity of supply and demand. The more inelastic the demand for water, the higher share of the burden is borne by buyers and vice versa when supply is more inelastic.

Figure 1: Influence of transaction cost on the water market equilibrium price and quantity d



The second case to consider is where agent *i* is a low value ag producer and assumed to be seller on the water market, $s_i > 0$ and $b_i = 0$. I assume the agent uses some of her water for production and only sells a portion of her endowment on the water market:

$$\begin{aligned} &P_y F_w(w_i, l_i) - c_w = \lambda_i \\ &P_w = \lambda_i \\ &\Rightarrow P_y F_w(w_i, l_i) - c_w = P_w \end{aligned} \tag{28}$$

Agent *i* will use water in production up to the point where the marginal value of water used in production equals the price of water on the water market, the remainder will be sold.

The last case to consider for a market with transaction costs is one in which no water is transferred:

$$
\begin{aligned}
&P_y F_w(w_i, l_i) - c_w = \lambda_i \\
&P_w + tc_b(b_i) < \lambda_i \\
&P_w < \lambda_i
\end{aligned}
\tag{29}
$$

agent *i* choose not to buy or sell water on the market because they will always be better off using their current water endowment in production and not participating in the water market. When transaction costs become sufficiently high, no water transfers will occur.

Municipal and Industrial Cost Minimization Problem

The M&I model with transaction costs is as follows:

$$\min_b C = P_w b_i + tc(b_i) \tag{30}$$

The constraints are the same as previously stated, resulting in the following Lagrangian:

$$L_i = P_w b_i + tc(b_i) + \lambda_i(\bar{w}_i + b_i - \text{baseline demand}_i) \tag{31}$$

The solutions to this problem are b_i^* and λ_i^* and satisfy the following first order conditions:

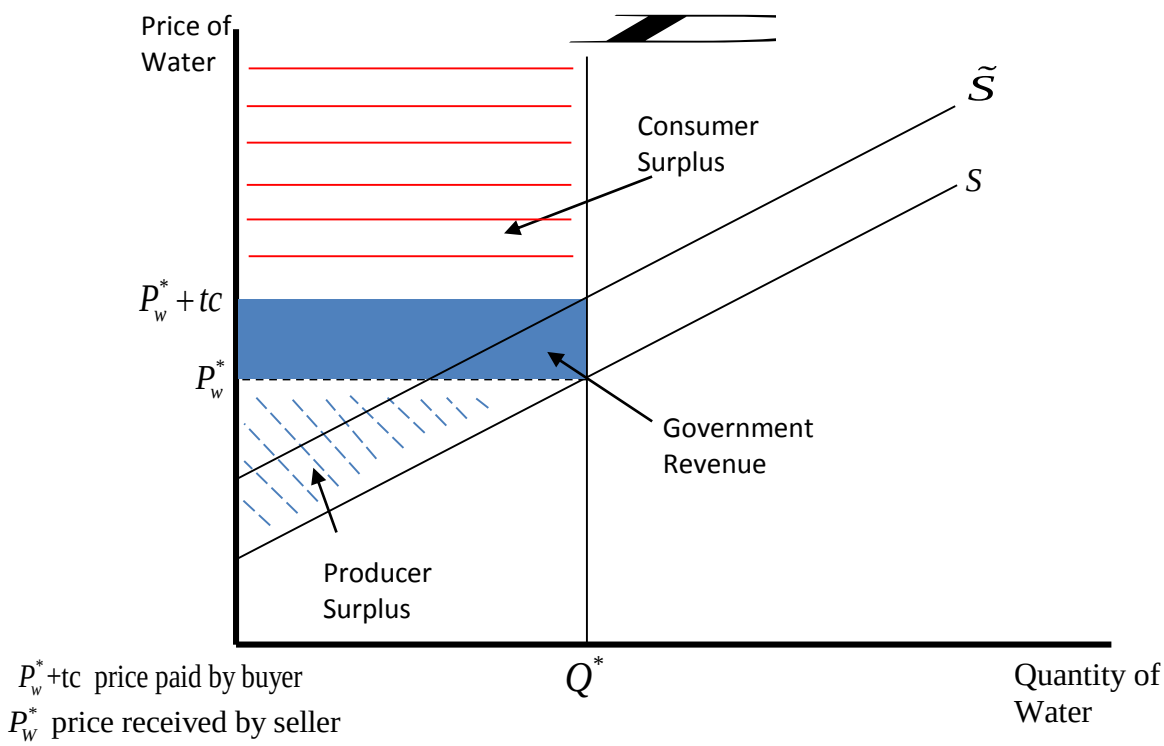
$$\frac{\partial L_i}{\partial b_i} = P_w + tc_b(b_i) + \lambda_i \geq 0 \qquad \text{c.s. } b_i \geq 0 \tag{32}$$

$$\frac{\partial L_i}{\partial \lambda_i} = \bar{w}_i + b_i - \text{baseline demand}_i \geq 0 \qquad \text{c.s.} \lambda_i \geq 0 \tag{33}$$

Similar to the producer problem, transaction costs increase the price of acquiring water on the water market and decrease the quantity purchased. The main difference between the impact of transaction costs on M&I and producer agents is due to differences in elasticity of demand for water. M&I agents have perfectly inelastic demand for water when there is one regional water market pool and producer agents have less inelastic demand. Figure two depicts the impact of transaction costs when demand for water is perfectly inelastic. Note that although the graph depicts transaction costs shifting the supply curve (i.e. paid by seller), results are the

same as if transaction costs are paid by the buyer. In the case of transaction costs, as with a tax, the party upon which the transaction cost/tax is levied does not impact results, the relative elasticity's determine who bears the burden. The buyer pays a higher price for water and bears the entire burden of the transaction cost. The seller receives the same price and the quantity of water exchanged remains unchanged.

Figure 2: Impact of transaction costs on market equilibrium with perfectly inelastic demand for water



Market Clearing Conditions

The market equilibrium price for the regional pool is defined by following condition:

$$\sum_i b_i = \sum_i s_i \tag{34}$$

Transaction costs influence the market clearing conditions by changing the amount of water transferred on the market and thus influencing the market clearing price. For the case in which agents exchange water on the water market, when transaction costs are present less water is transferred on the water market causing the price of water received by the seller to decrease from P_w^* to $\tilde{P}_w$ and of water paid by the buyer to increase from P_w^* to $\tilde{P}_w + tc$.

Baseline Model

Now that the simple model has been explored, I will add complexity to make the model more representative of a river basin by adding output type, region and time. First, I include output type for the producer, producers are assumed to produce a specific crop (it is not a choice). Second, I include five regions. Within regions, agents are assumed to be homogenous whereas across regions, agents are assumes to be heterogeneous. Transaction cost within and across regions will also differ. Including multiple outputs and region will make the model a more realistic representation of a river basin and thus, when populated with data, will provide welfare outcomes for the basin.

Lastly, I will include three time periods: short run, medium run, and long run. Time periods will enable me to analyze welfare outcomes under various population and climate change scenarios. Assumptions regarding availability of water and baseline demand will vary throughout time periods, but there will be no state variables. The model is simply run three separate times with different assumptions rather than being a dynamic model in which decisions in period one carryover to period two.

Producer Profit Maximization Problem

The baseline profit maximization problem for the producer is as follows:

$$\max_{w,l,s,b} \pi_i = \sum_t \left\{ \sum_y \left[P_{y,t} F(w_{i,y,r,t}, l_{i,y,r,t}) - c_{w,t} w_{i,y,r,t} - c_{l,t} l_{i,y} \right] + P_{w,t} s_{i_{r,t}} - P_{w,t} b_{i_{r,t}} \right\} \tag{35}$$

where $P_{y,t} =$ output price for *y* in time *t*, $F(\cdot) =$ production function describing output where $F(w,l) = f(w) \cdot l$, $w_{i,y,r,t} =$ water use by agent *i* to produce output *y* in region *r* at time *t*, $l_{i,y,r,t} =$ land use by agent *i* to produce output *y* in region *r* at time *t*, $c_{w,t} =$ cost of using water in production in time *t*, $c_{l,t} =$ cost of using land in production in time *t*, $P_{w,t} =$ price of water at time *t*, $s_{i_{r,t}} =$ the amount of water sold by agent *i* into regional pool *r* at time *t*, $b_{i_{r,t}} =$ the amount of water bought by agent *i* from regional pool *r* at time *t*.

The producer is subject to the following constraints:

$$\begin{aligned} & w_{i,y,r,t} \geq 0 \\ & l_{i,y,r,t} \geq 0 \\ & s_{i_{r,t}} \geq 0 \\ & b_{i_{r,t}} \geq 0 \\ & \sum_y w_{i,y,r,t} + s_{i_{r,t}} \leq \bar{w}_{i,r,t} + b_{i_{r,t}} \end{aligned} \tag{36}$$

where $\bar{w}_{i,r,t} =$ initial endowment of water for agent *i* in time *t* in region *r*.

Municipal and Industrial Cost Minimization Problem

The baseline cost minimization problem for the M&I agent is as follows:

$$\min_b C = \sum_t \left\{ P_{w,t} b_{i_{r,t}} \right\} \tag{37}$$

The agent seeks to minimize the cost of acquiring water subject to the following constraints:

$$\begin{aligned} & b_{i_{r,t}} \geq 0 \\ & \text{baseline demand}_{i,r,t} \leq \bar{w}_{i,r,t} + b_{i_{r,t}} \end{aligned} \tag{38}$$

where baseline demand$_{i,r,t}$ = the project demand for water for agent *i* in region *r* at time *t*, given current water use and population projections.

Market Clearing Conditions

The market equilibrium price for each regional pool is defined by following condition:

$$\sum_i b_{i_{r,t}} = \sum_i s_{i_{r,t}} \tag{39}$$

where there is a market clearing price associated with each region in each time period.

Model with Transaction Costs

The producer profit max problem with transaction costs is:

$$\max_{w,l,s,b} \pi_i = \sum_t \left\{ \sum_y \left[P_{y,t} F(w_{i,y,r,t}, l_{i,y,r,t}) - c_{w,t} w_{i,y,r,t} - c_{l,t} l_{i,y} \right] + P_{w,t} s_{i_{r,t}} - P_{w,t} b_{i_{r,t}} + tc(b_{i_{r,t}}) \right\} \tag{40}$$

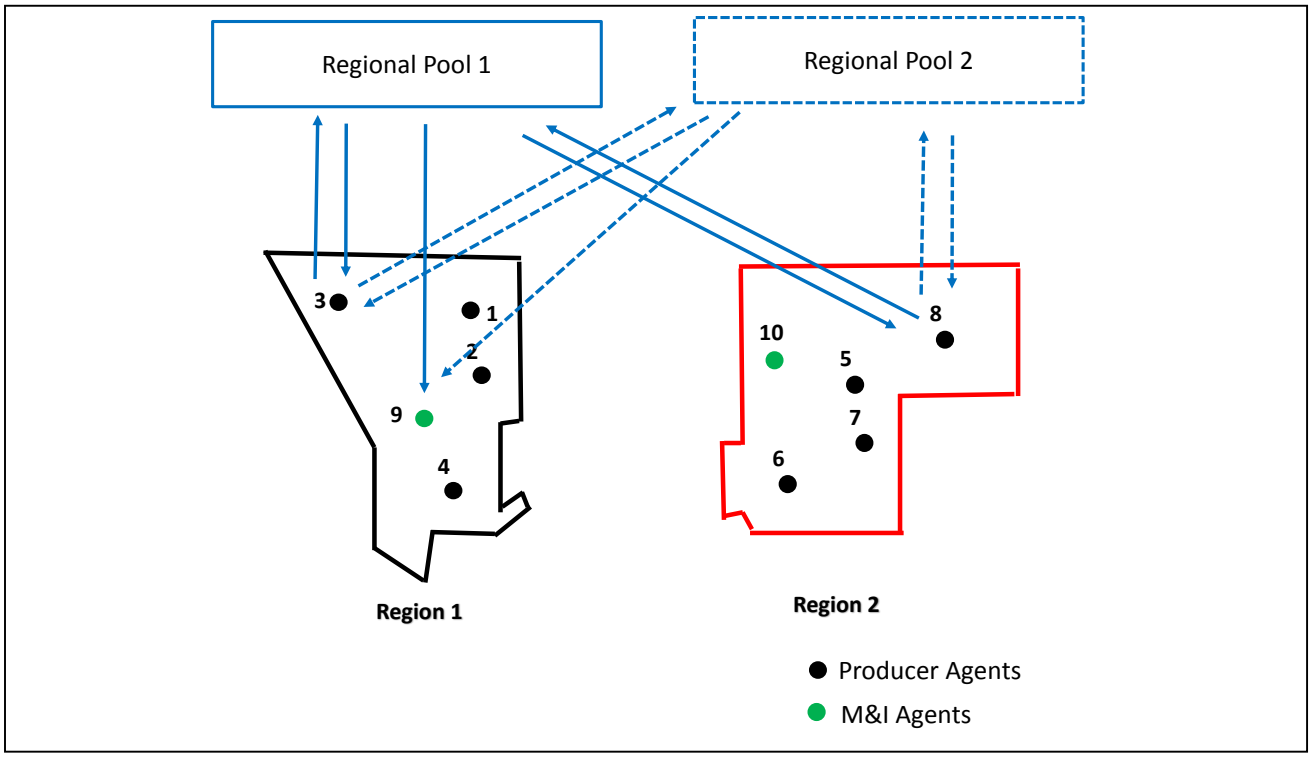
with the same constraints as previously stated. The M&I cost minimization problem with transaction costs is as follows:

$$\min_b C = \sum_t \left\{ P_{w,t} b_{i_{r,t}} + tc(b_{i_{r,t}}) \right\} \tag{41}$$

Market clearing conditions are the same as previously stated.

Figure 3 describes how transaction costs will be included in the model with multiple regions. Transaction costs vary across users based on location and mimic the idea that a buyer is located conveniently to some ditch companies but not others. Agents located in region one can buy and sell water from/into regional pool one with zero transaction costs (as if they are trading water within a ditch company). They can also buy and sell water from/into regional pool two, but will face a positive transaction costs (as if they are trading with a different ditch company).

Figure 3. Transaction costs with multiple regional pools



Empirical Model Specification

Numerical model simulation, based on data from the South Platte River in Colorado, will be used to compare welfare outcomes for agricultural producers and municipal water consumers in the region. The South Platte River Basin has one of the fastest growing populations in the 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 equations 40 and 41, 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) which allows me to model both the optimization problems of individual agents 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).

Data

I utilize secondary data as well as data from hydrologic, climate, and crop models to parameterize the model to represent the South Platte River Basin (SPRB) in Colorado. The SPRB is divided into five regions. The North region consists of Boulder, Broomfield, and Larimer counties and is characterized by having both agricultural and M&I agents and access to water from the Colorado Big Thomson Project (CB-T). 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 agents and some agricultural agents. The South Metro region includes Douglas, Elbert, and Park and is characterized by M&I agents that utilize ground water as well as a small number of agricultural producers that also utilize ground water. The East is the final region and includes Morgan, Logan, Sedgwick, and Washington and is characterized by having only agricultural agents. The temporal scale consists of 3 time periods: the short run (2015-2024), the medium run (2045-2054), and the long run (2090-2099).

Crop specific production functions are provided for each region from DAYCENT, a crop model parameterized to the SPRB. Crop prices are from National Agricultural Statistical Service (NASS) data. The input cost of land is from NASS data on the rental price of irrigated crop land and the input cost of using water for production is from Colorado State Extension Crop Budgets. There are two potential ways to calculate current endowment of water (i.e. water right amount) for producer agents. The first is to use the water rights records from the Colorado Division of Water Resources. The second would be to assume that producers are currently using their full endowment of water to produce crops. Given this assumption and the calculation of the irrigation water requirement for each agent by region, provided by DAYCENT, I can calculate the current endowment, or "firm yield" of water. Given the challenges associated with the water rights records, the latter approach is utilized. Current endowment of land is based on the land currently in production from NASS. Current endowment of M&I water rights will be calculated from current M&I water demand in each region. Most municipalities have some extra supplies of water, so this number is likely to be an underestimate of actual water rights holdings.

Future municipal demand is be calculated by the Integrated Urban Water Management Model (IUWM) model based on low, medium, and high population growth scenarios created by the Colorado Water Conservation Board using the population growth model from the Center for Business and Economic Forecasting and the Colorado State Demographer's Office. Data on production functions, firm yield, and future municipal demand is not yet available. For this model run, Cobb-Douglas production functions with roughly estimated parameters are used for production functions, and made-up data is used for the remaining parameters to demonstrate expected model results. For this model run, only two regions will be used.

The data consists of the following:

- 2 regional pools (i.e. ditch companies)
- 5 agents in each of the two regions (total of 10)
    - Agents 1-4 are producers, all with an initial endowment of 10 units of water
        - 1.1 (agent one in region one)
        - 1.2 (agent one in region two)
        - Etc.
    - Agent 5 is M&I, with an initial endowment of 4 units of water in region one and 8 in region two
- Ranking of marginal productivity of water in production
    - Agent 1
    - Agent 3
    - Agent 2
    - Agent 4
- M&I future demand
    - In region one, M&I demands additional 22 units water
    - In region two, no additional M&I demand

Preliminary Results

Preliminary results from the two region model without transaction costs is presented in Table 1, and with transaction costs in Table 2. Producers with higher marginal value of water in production (agent 1) use the most water in production, augmenting their initial endowment of water by purchasing water on the market from producers with a lower marginal value of water in

production. M&I users purchase the exact amount of water needed to meet future demand. The main difference between the two regions is in the M&I demand for water. The M&I agent located in region one demands an additional 19 units of water whereas the M&I agent in region two has no demand for water. Given the existence of transaction costs for buying water from outside the region, there is a higher demand to purchase water from regional pool one than there is for regional pool two. In the model with transaction costs, users pay zero transaction costs to purchase water from their own regional pool but face a transaction cost of $5 when buying water from the other regional pool.

Table 1: Preliminary results from two region model without transaction costs

Agent	Use	Sell to Pool 1	Sell to Pool 2	Buy from Pool 1	Buy from Pool 2
1.1	20.2	1.7	0.0	3.9	8.0
2.1	3.1	7.2	0.0	0.1	0.2
3.1	4.3	5.8	0.0	0.1	0.1
4.1	0.3	9.9	0.0	0.1	0.2
5.1	-	0.0	0.0	12.0	12.0
1.2	20.2	0.0	1.7	8.0	3.9
2.2	3.1	0.0	7.2	0.2	0.1
3.2	4.3	0.0	5.8	0.1	0.1
4.2	0.3	0.0	9.9	0.2	0.1
5.2	-	0.0	0.0	0.0	0.0
PW		10.2	10.2	10.2	10.2

Table 2: Preliminary results from two region model with transaction costs, tc=0 buying within regional pool, tc=5 buying from outside regional pool

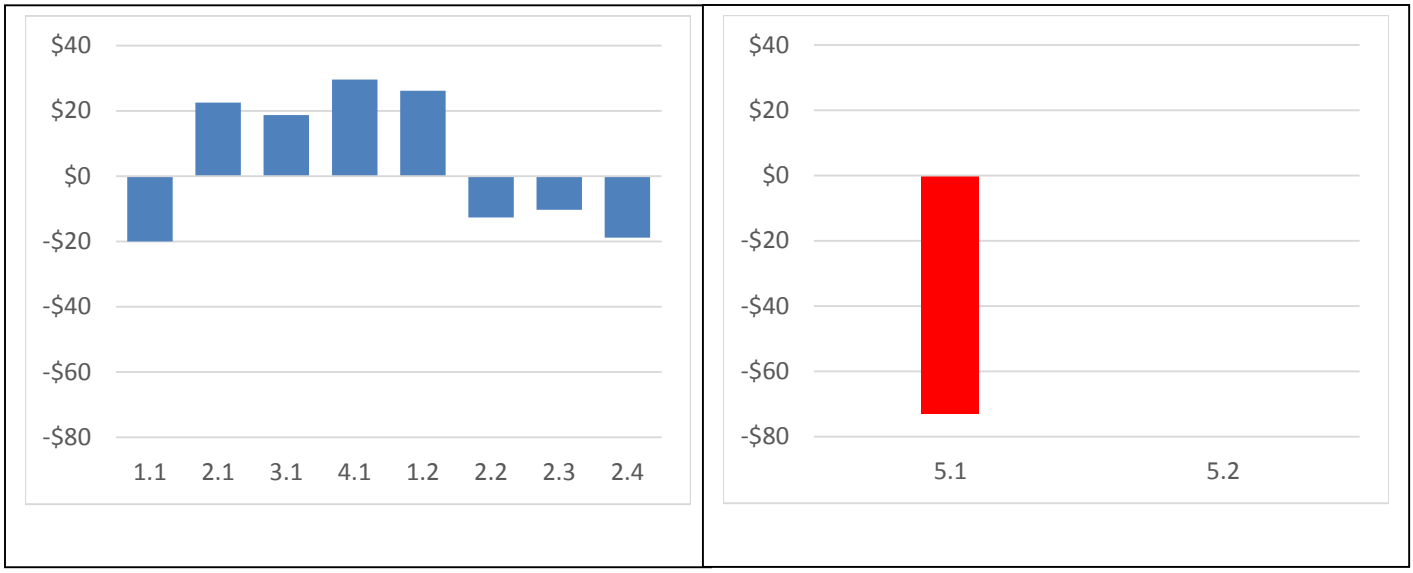
Agent	Use	Sell to Pool 1	Sell to Pool 2	Buy from Pool 1	Buy from Pool 2
1.1	13.5	1.1	0.0	3.9	0.7
2.1	2.2	8.8	0.0	0.4	0.5
3.1	3.4	6.8	0.0	0.1	0.1
4.1	0.3	9.9	0.0	0.1	0.2
5.1	-	0.0	0.0	22.1	1.9
1.2	27.0	0.0	0.6	0.0	17.6
2.2	4.0	0.0	6.1	0.0	0.1
3.2	5.2	0.0	4.9	0.0	0.0
4.2	0.4	0.0	9.8	0.0	0.2
5.2	-	0.0	0.0	0.0	0.0
PW		13.2	8.2	18.2	13.2

Use goes down in region one and up in region two. Region one has a higher demand for water than regional pool two. Both regions want to buy as much water as possible from their own region therefore the main buyer that is affected is the M&I agent. Since demand for water in regional pool one is higher, the price of water in regional pool one goes up and the price in regional pool two goes down. Now water is more valuable on the market than in production, so water used in production decreases in region one and increases in region two.

Figure 4 describes the change in welfare when transaction costs are introduced. Some agents gain from transaction costs while others lose. The biggest welfare loss is for the agents that buys the most water and the biggest gain is for the agent that sells the most water. Agent one in region one is a high value producer and is a water buyer. When transaction costs are introduced, competition for water in their region increases and the price of water in their regional pool goes up. The agent is not able to buy as much water as they were before and welfare decreases. The other agents in region one see welfare gains as they are water sellers and now can sell water for a higher price. Agent one in region two, also a water buyer, sees an increase in

welfare because the price of water in their regional pool decreases. The other agents in regional pool two are sellers of water and thus see a decrease in welfare due to a lower price. Consumer welfare decreases in region one as the M&I agent now has to pay a higher price for water yet must still acquire the same amount of water.

Figure 4. Change in welfare when transaction costs are introduced



Conclusion

Results from this paper show that heterogeneous agents and the existence of transaction costs do play a role in welfare outcomes from the water market, showing the importance of modeling imperfectly competitive water market to provide more nuanced policy and market analysis. As transaction costs increase, water is essentially more expensive. Because municipalities are going to acquire the same amount of water whether transaction costs exist or not, the quantity of water purchased by municipalities will be the same, they will just pay more for it thus reducing consumer welfare.

While the amount of water producers transfer to municipalities will not change, producers are likely to purchase less water from other producers as transaction costs increase,

thus decreasing producer welfare. Although these changes will depend on the marginal productivity of water, where transaction costs will impact high value and low value producers differently. Once parameterized, this model of the South Platte River Basin will allow policy makers to better understand welfare gains from reducing transaction costs, thus serving as a guide for what constitutes a reasonable investment of government resources to facilitate the reduction of transaction costs in the water market.

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