Gains from Water Markets: Micro-level Evidence on Agricultural Water Demand

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Abstract
This paper demonstrates that the establishment of well-functioning water markets may substantially mitigate the costs of drought. We develop a framework to model the costs of incomplete water regulation, and simulate the efficiency gains from water trading across the agricultural and urban sectors. Critical to this exercise are credible estimates of the price elasticity of demand for agricultural water. We use monthly panel data on well-level agricultural groundwater extraction in an area that charges volumetric rates for groundwater to estimate the elasticity. Demand is inelastic, with estimates ranging from -0.17 to -0.22. Our simulation suggests that in an agriculturally productive and dense urban area of California, a water market could have reduced the welfare impacts to residential users from the 2015 drought mandate by 60% from $83 million to $33.5 million. Water markets present a promising adaption strategy to climate change.

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1 Introduction

The theoretical prediction that efficiency costs arise from incomplete regulation has been empirically corroborated in a number of settings, including the management of environmental externalities. Incomplete regulation has limited the cost effectiveness of both market-based and non-market based approaches to manage carbon dioxide emissions and local air pollutants (e.g., Fowlie 2009; Baylis, Fullerton, and Karney 2013). One area where the costs from incomplete regulation may be particularly severe, yet little empirical evidence exists, is in the water sector.

Water markets may substantially mitigate the economic costs of climate change. Climate change is expected to cause warmer temperatures and more variable precipitation, including an increase in both droughts and floods (Kunkel et al. 2013; Swain et al. 2018). A growing literature has focused on quantifying the economic costs of warming temperatures, and evaluating policies to mitigate these costs (e.g., Deschênes and Greenstone, 2007; Costinot, Donaldson, and Smith 2016). Less well understood are the impacts of climate change on water supplies, and in particular, instruments available to mitigate these potential costs. This paper develops and implements a framework to analyze the welfare costs from the establishment of water markets that would allow for water trading across urban and agricultural consumers. It proceeds in three steps: the development of a simple theoretical framework to model the gains from trade; the estimation of the price elasticity of demand for agricultural water using rich, micro-level panel data; and a simulation that leans heavily on our demand estimation to quantify the gains from trade.

We begin by setting forth a simple theoretical model of water trading between agricultural and urban users to estimate the gains from trade. This model provides a template with which to formalize the relationship between water allocations and the gains from trade. We then impose structure on this model to derive an analytical solution to the gains from trade. This allows us to quantify the benefits from trade as a function of observables and estimated parameters,
and stands in contrast to earlier work that relies on mathematical programming techniques to measure the efficiency gains (e.g., Sunding et al. 2002).

The primary challenge to estimating the gains from trade is the absence of micro-level evidence on the marginal value that agricultural users attach to water. A first obstacle is the paucity of data on agricultural water use at a temporal and cross-sectional scale necessary for credible estimation. Where these data do exist, a second obstacle arises due to the absence of prices for water. For these reasons, existing estimates on the marginal value of agricultural water rely on aggregate measures of water or proxies for water prices (e.g. Pfeiffer and Lin 2014; Hendricks and Peterson 2012; Gonzalez-Alvarez, Keeler, and Mullen 2006). This paper overcomes both of these empirical hurdles by taking advantage of monthly, well-level data on irrigation water spanning 17 years in a jurisdiction that charges prices for agricultural water.

We estimate the price elasticity of demand for agricultural water in the Coachella Valley Water District, a productive agricultural region in southern California that deploys three different tariff structures for groundwater extraction. Three features of this empirical setting give rise to a research design that allows for direct estimates of the short-run price elasticity of agricultural groundwater. First, this water district charges all well users a volumetric rate for groundwater, thus allowing for direct estimates of the relationship between observed water prices and groundwater demand. Second, three distinct geographically-based pricing regimes exist within this single water district. Third, we show that assignment to a pricing regime is uncorrelated with baseline water use, and changes in prices over time are unrelated to time-varying regional observables. The quasi-random assignment of different volumetric rates for groundwater to all the groundwater wells within a single water district allows for the direct estimation of the relationship between water prices and agricultural water demand.

A key empirical result is that the short-run demand for agricultural groundwater exhibits a relatively inelastic response to changing water prices. Controlling for fixed well-level and aggregate seasonal unobservables, we estimate a price elasticity of -0.17. These results are robust to the inclusion of regional time-varying observables that might be systematically correlated.
with both groundwater extraction and regional prices, and to the exclusion of residential wells.

This price elasticity estimate is both the relevant and a necessary parameter to quantify the efficiency gains from the implementation of water markets. While our estimate of the price elasticity of demand for agricultural groundwater is similar in magnitude to recent empirical work on the topic, it differs in interpretation along important dimensions (e.g., Pfeiffer and Lin 2014; Hendricks and Peterson 2012; Gonzalez-Alvarez, Keeler, and Mullen 2006). Previous studies lean on energy prices and groundwater depth to measure extraction costs and estimate an elasticity comprised of both the intensive and extensive margins. In contrast, we provide the first micro-level estimate of the effect of volumetric groundwater prices on groundwater demand. This serves as a comparable counterpoint to urban price elasticity estimates that use volumetric prices, as opposed to energy prices and groundwater depth as proxies for price. The existence of volumetric groundwater prices also allows for the estimation of a price response that overcomes attenuation and amplification bias due to incomplete information on energy costs to extract groundwater (Mieno and Brozovic 2017).

Riverside County in southern California provides a policy-relevant and ideal research setting in which to evaluate the potential efficiency gains from the introduction of water trading between agricultural and urban users. From a policy perspective, it is home to both a productive agricultural region that faces unique, volumetric prices for groundwater and a large urban population that experienced a mandated curtailment in use during the last drought. From a research design perspective, our choice to focus on the gains to trade in a single geographic and political jurisdiction supplied by the same, shared aquifer overcomes the empirical difficulty of disentangling efficiency gains from transaction costs. Substantial transaction costs are involved with the exchange of water across political boundaries and the transport and movement of water, and it is difficult to know ex-ante if these costs will exceed the efficiency gains (Hagerty 2017; Regnacq, Dinar, and Hanak 2016). We study the gains from trade in a setting where administrative and physical transaction costs will be minimal. A final advantage of our simulation is that all parameters are either estimated or observed for Riverside County. In sum, our
empirical setting is endowed with a number of features that make it ripe for a policy relevant and transparent measure of the potential gains from agricultural to urban water trades.

Our simulation highlights that the welfare costs to users of a 25% mandatory reduction in urban water use could have been reduced by 80%, a reduction of $68 million, in the presence of a well-functioning water market. Under an assumption of costless bargaining, we find that 77% percent of the mandatory reduction in water use would have occurred through a reduction in agricultural water use. The benefits from the introduction of water markets to residential users in the City of Riverside are large, reducing the welfare costs of compliance with the drought mandate by 60%. Agricultural users in the Coachella Valley also benefit, with an increase in surplus of $19 million. We conclude that providing urban and agricultural users with flexibility in how to comply with water conservation mandates will substantially reduce the costs of drought.

2 Theoretical Framework for Water Trading

In this section, we implement a simple theoretical framework to evaluate the efficiency gains from the establishment of a water market that allows for trade between urban and agricultural users. We begin by considering a status quo in which mandatory water restrictions are placed on urban users, and trade is prohibited. We then model a policy in which restrictions are again imposed on urban water users, but regulation is complete and water trading is permitted between agricultural and urban users. We first illustrate the gains from trade using a simple conceptual framework. To quantify the gains from complete regulation, we then impose some structure on this conceptual framework and obtain analytical solutions.

Consider a market comprised of two types of users - an agricultural water (type A) and an urban water (type U) - that consume water from a single source. Assume that users are homogeneous within their type, agricultural users are a low-demand water type, and residential users are a high-demand water type. Let $P = D_U(x)$ and $P = D_A(x)$ denote the inverse aggregate
Figure 1: Urban and Agricultural Water Demand

Notes: $D_A$ and $D_U$ denote inverse aggregate demand curves for agricultural and urban water, respectively. $x^*_i$ denote the unconstrained optimal quantities of water demanded. $E_i$ for $i \in A,U$ represent water allocations to each section, reflecting a restriction of $z\%$ to the urban sector.

Demand curves for urban and agricultural water, respectively, where $x$ represents the quantity of water demanded. Given a constant marginal cost of consumption, $c$, the agricultural sector’s quantity demanded is $x^*_A$ and the urban sector’s quantity demanded is $x^*_U$. Figure 1 illustrates the inverse demand curves and quantity demanded given a marginal cost of consumption.

Now suppose the regulator imposes a mandatory $z\%$ reduction in aggregate business-as-usual water use for all urban consumers, but no restriction on agricultural water use. As shown in Figure 1, this results in an allocation of urban water use, denoted by $E_U$, equal to $(1 - .z)x^*_U$. Agricultural use remains unconstrained, so the effective allocation of water equals the optimal
Notes: The left figure depicts the aggregate surplus for urban consumers under a policy that restricts aggregate urban water use by \( z\% \). The right figure depicts the unconstrained, aggregate surplus for agricultural users. The shaded areas illustrate the total net benefits if regulation is incomplete and trade between sectors is prohibited.

Consumption at marginal cost \( c \), \( E_A = x_A^* \).

First consider the total net benefits if regulation is incomplete and trade between agricultural and urban users is prohibited. The vertical line emerging from the point \( E_U = (1 - z)x_U^* \) corresponds to an allocation in which urban water use is reduced by \( z\% \). Agricultural water use remains at \( E_A = x_A^* \). Figure 2 illustrates the surplus under this urban curtailment when trade is prohibited. The total net benefits (\( TNB \)) associated with this policy are given by,

\[
TNB = \int_0^{E_U} D_U(\tau) d\tau - cE_U + \int_0^{E_A} D_A(\tau) d\tau - cE_A,
\]

which is shown by the sum of the shaded areas in Figure 2.

Now, imagine that the market is complete and water trades can occur between urban and agricultural users. If the marginal value product for urban consumption at the constraint is greater than the marginal value product for agriculture at the unconstrained optimum, then there exists some set of prices where trading will occur. Let us define \( p^T \) as the market-clearing price for water trades and \( x_A^T \) and \( x_U^T \) as the quantities of water where \( D_A(x_A^T) = D_U(x_U^T) = p^T \).
These latter quantities describe the quantity consumed by each type after trade. The difference between $E_A$ and $x_A^T$, or equivalently the difference between $x_U^T$ and $E_U$, determines the quantity of water traded.

We express this trading scenario in an Edgeworth-box style figure, which is equivalent to Figure 1. As shown in Figure 3, the width of the horizontal axis, $E_A + E_U = x_A^* + (1 - x) x_U^*$, measures the total allocation of water across both agricultural and urban users. Any point along the x-axis represents a different combination of allocations across the two sectors. Moving left-to-right, the horizontal axis measures urban water use and moving right-to-left, it measures agricultural water use. As shown in Figure 3, trade will occur until marginal net benefits are equal across the two sectors, which is represented by the intersection of the two demand curves. The shaded triangle illustrates the gains from trade given initial allocations of $E_A$ and $E_U$, which reflect a status quo where all abatement is expected to come from urban water use.

Mathematically, these gains from trade can be expressed as the area,

$$G = \int_{(1 - x)T_U}^{x_U^T} D_U(\tau) d\tau - \int_{x_A^*}^{x^T_A} D_A(\tau) d\tau,$$

which depends on the shape of the demand curves, the initial allocations, and the magnitude of the curtailment in urban use.

2.1 Analytical Framework

To obtain analytical solutions, we impose functional forms for the demand curves that exhibit constant slopes, where $P(x_U) = \gamma_U - \sigma x_U$ for urban water and $P(x_A) = \gamma_A - \alpha x_A$ for agricultural water,

$$G = \int_{(1 - x)T_U}^{x_U^T} (\gamma_U - \sigma \tau) d\tau - \int_{x_A^*}^{x^T_A} (\gamma_A - \alpha \tau) d\tau.$$

We can integrate this expression and solve for the gains as a function of parameters, the equilibrium quantity of water consumed by each type after trade, $x_A^T$ and $x_U^T$, and the unconstrained
Figure 3: Gains from Ag-Urban Trade

Notes: $D_A$ and $D_U$ denote inverse aggregate demand curves for agricultural and urban water, respectively. $x_i^*$ denote the unconstrained optimal quantities of water demanded and $E_i$ denote allocations to each sector. The total allocation is fixed on the x-axis and any point along the axis represents a different allocation between types. The triangle represents the gains from trade.
optimal quantities of water demanded by each type, $x_A^*$ and $x_U^*$:

$$G = \gamma_U(x_U^T - E_U) - \gamma_A(E_A - x_A^T) - \frac{\sigma}{2}(x_U^{T^2} - E_U^2) + \frac{\alpha}{2}(E_A^2 - x_A^{T^2}).$$  \hspace{1cm} (4)

To solve for the optimal quantity of water use by agricultural and urban sectors after trade ($x_A^T$ and $x_U^T$), we make use of the relationship between the water allocated and consumed in these sectors, which is given by $x_A^T + x_U^T = E_U + E_A$. We then equate $\gamma_U - \sigma x_U = \gamma_A - \alpha x_A$ and we solve the system of two equations in two unknowns:

$$x_A^T = \frac{\gamma_A - \gamma_U + \sigma(E_U + E_A)}{\alpha + \sigma}, \hspace{1cm} (5)$$

$$x_U^T = \frac{\gamma_U - \gamma_A + \alpha(E_U + E_A)}{\alpha + \sigma}. \hspace{1cm} (6)$$

These expressions also allow for the solution to the equilibrium market price,

$$p^T = \gamma_U - \sigma \left(\frac{\gamma_U - \gamma_A + \alpha(E_U + E_A)}{\alpha + \sigma}\right). \hspace{1cm} (7)$$

Imposing this simple structure on the aggregate urban and agricultural demand curves allows us to solve for equilibrium quantities and prices as a function of demand parameters and the initial endowments of water.

3 Background

Riverside County, identified on a map of California counties in Figure 4, provides an ideal setting in which to evaluate the efficiency gains from the establishment of a water market comprised of agricultural and urban users. The county is home to both a productive agricultural region, with revenues over half a billion annually, and a large urban area, with a population of over 2.36 million people. One irrigation district in the county charges volumetric rates for agricultural groundwater use. Furthermore, residential users experienced a mandatory 25% curtailment
in aggregate water use during the 2015 drought. The combination of volumetric pricing for agricultural and urban water users, and the introduction of temporary but mandatory urban water restrictions provides a policy-relevant study in which to begin to understand the gains from complete regulation of water.

3.1 Urban Water Use: City of Riverside

We use the City of Riverside as the empirical setting in which to understand the price elasticity of demand for urban groundwater. Riverside Public Utilities (RPU) serves the greatest population among the water utilities in Riverside county, covering 70 square miles within the City of Riverside and 5 additional square miles within the County. RPU operates nearly 60 groundwater wells as the primary water source for their 300,000 urban consumers, supplying 75,000 AF of water in 2015 (RPU, 2016).
3.2 Agricultural Water Use: Coachella Valley

We use the Coachella Valley Water District (CVWD), the largest water agency in the Coachella Valley, to evaluate the price elasticity of demand for agricultural groundwater. This productive agriculture region is located in Riverside County, just north of the Salton Sea and southeast of the San Bernardino Mountains. It depends heavily on groundwater and Colorado River water for irrigation, and has roughly 65,000 acres in crop production with a total production value of over half a billion dollars a year. The area produces 95% of the nation’s dates, as well as table grapes, citrus fruits, bell peppers, and other vegetables.

A unique feature of the CVWD is that it charges volumetric prices to pump groundwater, and deploys three location-specific rates within its district. Figure 5 depicts a map of the CVWD and the boundaries that delineate each pricing region: East Whitewater, West Whitewater and Mission Creek. Within each geographic region, all customers face a uniform price per acre-foot for groundwater extraction, called the Replenishment Assessment Charge (RAC). The revenue collected from these tariffs is used to fund the artificial replenishment of the aquifer using surface water imports from the Colorado River, which benefits farmers that rely on groundwater for irrigation. Volumetric pricing of agricultural groundwater contrasts with the pricing structure implemented across most water districts in California and the U.S. Most agricultural users that rely on groundwater for irrigation do not face a price for groundwater extraction beyond the energy costs incurred from lifting the groundwater from the aquifer to the surface.

Several factors characterizing water use in the CVWD complicate the relationship between groundwater prices and agricultural groundwater use. First, most but not all groundwater users also have access to surface water. This is delivered from the Colorado River and transported to the artificial replenishment facilities and customers through the Coachella Canal. Surface water deliveries occur periodically and the quantities delivered may vary due to drought conditions. The canal rates charged to customers for surface water are volumetric and vary by user type (e.g. agricultural, municipal) as opposed to location. Later in our discussion of the empirical approach, we make explicit how we control for the possibility that surface water rates and
Figure 5: Areas of Benefit in Coachella Valley

Notes: This figure displays the boundaries of CVWD’s three distinct service regions: East Whitewater, West Whitewater, and Mission Creek. Source: Coachella Valley Water District.
deliveries may be systematically correlated with both groundwater prices and groundwater use.

The diverse set of groundwater users in the Coachella Valley also impacts the analysis of the relationship between prices and agricultural water use, and the interpretation of our results. In CVWD, groundwater use spans agricultural, urban, and recreational uses. As of 2005, 45% of water use came from the agricultural sector, 33% of water use came from urban (residential and industrial) users, and 17% of water was used by golf courses (Coachella Valley Water District, 2012). While well-level data on water use do exist, they do not indicate user type. This makes it impossible, in the absence of exact geographical coordinates, to segregate agricultural wells from other well types. We are able to make coarse approximations as to the locations where agriculture is most likely to occur, and assess the robustness of our results to alternative samples.

4 Data

Monthly well-level data on agricultural groundwater extraction and regional information on volumetric groundwater prices serve as primary data to estimate the price elasticity of demand for agricultural groundwater. These are supplemented by datasets on weather, drought, surface water deliveries, and quantities of groundwater recharge. Table 4 provides descriptive statistics, including the unit of observation and data source for each variable.

For the years spanning 2000 to 2016, the Coachella Valley Water District provided monthly groundwater extraction for all 900 wells subject to volumetric pricing. These data form an unbalanced panel of monthly well-level groundwater extraction, where the imbalance in the panel reflects the addition of new wells to the program over time. Figure 6 plots average monthly groundwater use for each unique pricing region over time. This figure makes clear the temporal and cross-sectional variation in groundwater use. We observe strong seasonal patterns in groundwater use, with extraction peaking in the summer and reaching a trough in the wet and

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1 This is the most recent year that data separating out aggregate water use by user type are available.
2 Wells that extract less than 25 AF per year are not charged a volumetric price for groundwater.
## Table 1: Descriptive Statistics

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<tr>
<th></th>
<th>Obs</th>
<th>Unit of Obs</th>
<th>Mean</th>
<th>SD</th>
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<th>Max</th>
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<td>Groundwater Extraction (AF)</td>
<td>6424</td>
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<td>0.42</td>
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<td>Region-Year</td>
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<td>0.70</td>
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<td>0.07</td>
<td>0.08</td>
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<td>State Water Deliveries (%)</td>
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<td>14</td>
<td>Year</td>
<td>54837</td>
<td>3693</td>
<td>43613</td>
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<td>Proportion Citrus</td>
<td>14</td>
<td>Year</td>
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<td>0.03</td>
<td>0.13</td>
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<td>14</td>
<td>Year</td>
<td>0.27</td>
<td>0.02</td>
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<td>Year</td>
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<td>0.04</td>
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<td>Year</td>
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<td>0.01</td>
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<td>Year</td>
<td>0.06</td>
<td>0.01</td>
<td>0.05</td>
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Notes: This table shows observations, means and standard deviations for well-month, region-month, region-year and month covariates. The drought indices give the percentage of land in Riverside County experiencing different degrees of dryness from Drought Index 0 representing "abnormally dry" conditions up to Drought Index 4 representing "exceptional drought" conditions.
dormant month of January. A visual inspection also reveals meaningful differences in the levels of use across regions, and changes in water use across regions over time. Groundwater extraction declines dramatically over time in the East and in Mission Creek and remains relatively unchanged in the West. Differences in levels and changes in extraction may occur because of differences in land use, prices, the availability of surface water, or other factors.

Figure 7 plots the monthly volumetric price charged per acre-foot in each region. All customers within a region face a uniform price per acre-foot for groundwater extraction, where this price varies at the region-year only. When price changes do occur, these changes take effect in the same month of the year - July - across all regions. While the timing of the rate change is shared across regions, the actual rate change differs substantially across regions.
Figure 7: Volumetric Groundwater Prices by Region

Notes: The figure shows volumetric groundwater prices by region over time.
The plot of regional prices over time illustrates a number of important features about volumetric pricing in the Coachella Valley. First, it highlights that volumetric pricing was introduced at different dates in each region. It was implemented prior to 2000 in the West, in July 2004 in Mission Creek and in January 2005 in East Whitewater. The staggering of the implementation of volumetric pricing across regions leads to a setting in which for two districts we observe monthly, well-level groundwater use during months in which the price is zero. Second, there is a clear increasing trend in volumetric rates across all three regions, and there are also substantial regional differences in prices and changes in prices. For example, there exist years when rates change for the East region, but for no other region. Third, a comparison across Figures 6 and 7 suggests no obvious patterns between prices and groundwater extraction—the highest quantities of extraction and prices are observed in the West, and the lowest quantities of extraction and lowest prices are observed in the East.

To account for the possibility that groundwater extraction and prices may be correlated with surface or recycled water supplies, groundwater recharge, or land use, we obtained monthly or annual data on these variables. As shown in Table 4, recycled water deliveries and the quantity of groundwater recharged vary at the region-year level. This information was reported in documents published by the water district (CVWD, 2016). Surface water use is measured for the water district at the monthly level. Monthly consumptive use of surface water diverted from the Colorado River for direct use is reported by the Bureau of Reclamation and represents surface water use on behalf of all users in the service area of the Coachella Valley Water District (U.S. Department of Interior, 2017). We also collected information on the percentage of surface water delivered throughout California in a given year via the State Water Project. The California Department of Water Resource’s State Water Project allocation announcements, which range from 0-100% of the quantities requested in State Water Project surface water contracts, may represent aggregate shocks that influence the amount of water available to groundwater replenishment facilities within CVWD’s service area. Lastly, annual land use data were collected from Coachella Valley’s acreage and agricultural crop reports, which describe
total irrigated acreage and the percentage of land in various crop categories.

We also collected data on drought and aggregate weather shocks to address the possibility that precipitation may affect groundwater extraction and prices over time. Daily precipitation and temperature data were collected from a weather station at the Indio Fire Station (National Climatic Data Center #4259) in Riverside county. Daily precipitation data were summed to aggregate to the monthly level. Growing degree day and harmful degree day variables were constructed from daily average temperatures and used in place of temperature\(^3\) Lastly, monthly values of the U.S. Drought Monitor Index for Riverside County were collected over the relevant time period (U.S. Department of Agriculture, 2017). D0 represents the percentage of land in Riverside County facing "abnormally dry" conditions in a given year. D4 is the most extreme degree of drought, representing conditions of "exceptional drought". All are expressed as a percentage of land coverage in that category.

5 Empirical Framework

The deployment of three different volumetric pricing regimes for groundwater extraction within a single water district provides an opportunity to more credibly estimate the price elasticity of demand for agricultural water. This is because our research design eliminates the need to construct an imperfect and potentially endogenous measure of groundwater prices, and our econometric approach is able to control for a rich array of unobservables and observables that may confound estimation of the price elasticity. In what follows, we detail the research design, provide support for the plausibility of the main identifying assumptions, lay out our econometric specification, and present results.

\(^3\) Agronomists model temperature by converting daily temperatures to growing degree days, a nonlinear transformation of temperature that more accurately reflects the way crops respond to heat. Growing degree days are derived by summing the degrees above a lower baseline and below an upper threshold during the growing season. Following Richie and NeSmith (1991) and Schlenker, Hanemann, and Fisher (2007), we use the range from 8\(^\circ\)C to 32\(^\circ\)C, within which plant growth is assumed to be linear. Days with temperatures above 34\(^\circ\)C, assumed to be harmful to plant growth, are used to construct harmful degree days.
5.1 Research Design

Credible estimation of the impact of volumetric prices on groundwater extraction relies on the assumptions that assignment to a pricing regime and changes in regional groundwater prices over time are independent of potential outcomes. We now discuss the process by which wells were assigned to treatment, and provide empirical evidence that suggests that this assignment mechanism is independent of baseline groundwater use. We then describe the determinants of regional prices and price changes, and make explicit time-varying regional and aggregate factors that may confound estimation of the price elasticity of demand.

5.1.1 Assignment of Wells to Treatment

The underlying hydrology in the CVWD determined the boundaries of the three unique groundwater pricing regions—East Whitewater, Mission Creek, and West Whitewater. It is assumed that the flow of groundwater from an artificial recharge site differs across regions but is similar within a region. These differences in flows suggest that each region may be characterized by different pressures and depths, but that these characteristics are the same across all wells within the same region.

The concern surrounding this assignment mechanism is that regions may be systematically correlated with both water use and the cost of groundwater extraction. As an example, if a lot of groundwater recharge occurs in one region, then the depth to the water table may be shallower and the available groundwater cheaper to extract than in a region with relatively lower artificial recharge. These differences will lead to differences in pumping costs and expected water supplies, and may subsequently impact the quantity of groundwater extracted, the acreage irrigated, and the choice of crops grown. Our empirical approach directly accounts for the possibility that fixed systematic differences may exist across pricing regimes through the inclusion of well fixed effects.

Though our estimation of the price elasticity of demand allows for the possibility that fixed regional differences may exist, we now provide empirical evidence consistent with the
assumption that the assignment of wells to a region is independent of potential outcomes. To do this we compare average monthly baseline water use, defined as 48 months spanning January 2000 - December 2003, across regions. We begin with a comparison of mean groundwater use across the Mission Creek and the East Whitewater regions, since these two regions faced a volumetric price of zero during this time period. Wells located in Mission Creek first incurred a volumetric charge in July 2004, and those located in the East were charged a positive volumetric rate beginning in January 2005. Figure 8 illustrates mean monthly regional water use and the difference in extraction across the two regions with 95% confidence intervals. It shows that no significant differences in average monthly groundwater use exist across regions prior to the introduction of volumetric pricing.

We next compare average conditional monthly groundwater use across the West and East regions for the same time period in Figure 9. One complication in this comparison is that wells in the West faced a positive price during these months. However, this comparison is the more relevant one since wells from these two regions comprise roughly 98% of our sample. To account for this, we condition on volumetric prices and then plot out the differences in mean monthly residual water use across the two regions. We also illustrate average monthly residual groundwater use in each region. We find that while in most months conditional water use is balanced across the regions, some differences exist as well. In January, average groundwater extraction in the East exceeds extraction in the West, while in June, use in the West exceeds use in the East. To the extent that these differences are driven by fixed regional characteristics, our empirical approach controls for them. Taken together, Figures 8 and 9 suggest that assignment of wells to regions is independent of water use.

5.1.2 Determination of Prices

An institutional exploration into the determinants of prices and price changes explains how they are set, and provides guidance into regional and aggregate time-varying factors that may be correlated with both prices and groundwater extraction.
Notes: The upper panel plots the difference in mean monthly groundwater use between the East Whitewater and Mission Creek groups in the pre-treatment period, 2000-2003. Neither region faced a positive price for groundwater during this time period. The vertical lines are 95% confidence intervals. The lower panel plots baseline groundwater extraction by month for the 4 pre-treatment years.
Figure 9: Pre-treatment Comparison between East and West

Notes: The upper panel plots the difference in mean monthly groundwater use conditional on prices across the East and West Whitewater groups in the pre-treatment period, 2000-2003. The vertical lines are 95% confidence intervals. The lower panel plots baseline groundwater extraction by month for the 4 pre-treatment years.
Revenues collected from groundwater pumping fund the CVWD’s Groundwater Replenishment Program, which artificially replenishes the aquifer at sites in each of the three regions. Regional differences in volumetric prices occur because the costs to implement this program differ across the three regions. The main driver of regional costs is the source of surface water used for groundwater recharge. Differences in the source of surface water partly explain why the East Whitewater region, relative to the other two regions, faces a lower volumetric price for groundwater. While the source of surface water for recharge is a major determinant of a groundwater prices, this source has no impact on well-level groundwater extraction except through the channel of prices. This suggests that the primary determinant of groundwater prices is unlikely to bias our estimate of the price elasticity of demand.

Changes in regional prices occur primarily because of changes in the aforementioned program costs and/or in regional groundwater production. The former costs include labor and equipment, administrative costs, and costs associated with the source and quantity of surface water used for artificial recharge. The quantity of surface water used for artificial recharge may be systematically related to groundwater extraction, if for example, this quantity impacts the depth to the groundwater table. Our empirical approach will condition on the quantity of surface water used for artificial recharge in each region-year.

5.2 Estimation and Identification

To estimate the price-elasticity of water demand for irrigated agriculture, we begin by using well-level panel data spanning 17 years to estimate a fixed effects model using OLS,

\[
w_{it} = \gamma_i + \beta P_{st} + \delta_t + \epsilon_{it}. \tag{8}
\]

The dependent variable, \(w_{it}\), is the natural log of groundwater extraction for well \(i\) in month \(t\). Our regressor of interest, \(P_{st}\), is the natural log of the volumetric price of groundwater in region \(s\) and month \(t\). To account for the possibility that fixed regional and well characteristics may
be systematically correlated with both prices and groundwater use, our specification conditions on well fixed effects, $\gamma_i$. Month-of-year fixed effects, denoted by $\delta_t$, are included to account for strong seasonal patterns in groundwater extraction. Lastly, $\epsilon_{it}$ is an idiosyncratic error term. Standard errors are clustered at the well level to allow for serial correlation within a well over time.

Of importance is the omission of month-by-year or year fixed effects from this regression. In our setting, prices change annually and in the same month of the year for each region. While there exists some year-to-year variation in prices across regions, the inclusion of year or month-year fixed effects explain most of the overall variation in year-to-year price changes. We are concerned that the identifying variation that remains after the inclusion of these richer time controls is insufficient to make plausible inference into the relationship between prices and groundwater demand.

However, the exclusion of these controls also poses an empirical concern. For the coefficient of interest $\beta$ to capture the causal effect of price changes on groundwater use, time-varying unobservables that impact extraction cannot be systematically correlated with prices. In our setting, aggregate shocks such as local elections, or month-by-year shocks, such as droughts or surface water use, may be systematically correlated with both prices and groundwater use.

To balance this tension between sufficient identifying variation and omitted variables bias, we proceed by augmenting equation 8 to explicitly condition on aggregate and regional time-varying observables that may be systematically correlated with both prices and extraction,

$$w_{it} = \gamma_i + \beta P_{st} + \omega X_{st} + \rho X_t + \delta_t + \epsilon_{it}. \quad (9)$$

The quantity of regional groundwater replenished in each year is captured in $X_{st}$. Conditioning on annual groundwater recharge by region addresses the empirical concern that prices are a reflection of this quantity, and that recharge quantities may also impact extraction. Aggregate time-varying observables, including precipitation, the drought index, temperature, surface water
use, and the annual measures of state water deliveries, are denoted by $X_t$. Since drought and weather may affect both groundwater use and prices, we control for precipitation, degree days, and the percentage of land in Riverside county facing different levels of drought. Surface water use and state water deliveries may also influence both groundwater prices and groundwater extraction.

Identification of the price elasticity of demand for agricultural groundwater comes from within-region deviations in groundwater prices, netting out price changes related to groundwater or alternative water supplies, weather, and land use. It rests on the assumption that, conditional on well fixed effects and a rich set of aggregate and regional time-varying observables, time-varying unobservables, including both aggregate annual shocks and monthly regional changes that impact extraction, are uncorrelated with prices.

While we cannot demonstrate that this identifying assumption holds, we offer two strategies to examine its plausibility. First, we test the sensitivity of our estimates of $\beta$ to the inclusion and exclusion of the time-varying observables included in $X_t$ and $X_{st}$. While our empirical approach is deliberate in conditioning on surface water consumption, surface water supplies, groundwater replenishment and drought conditions, one indication that price may be correlated with unobservables that impact water use is if the relationship between price and groundwater use is sensitive to the inclusion or exclusion of these observables. Second, we examine the robustness of our results to a number of potential confounding factors, including changes in land use, linear and quadratic time trends, lagged groundwater prices and electricity prices. We also test the robustness of our results to the monthly quantity of recycled water delivered to each region. The inclusion of the amount of recycled water delivered to each region controls for the possibility that recycled water may serve as a substitute for groundwater use, and that the CVWD may use volumetric groundwater prices as a way to fund recycled water deliveries.
6 Results

Results from the estimation of equations (8) and (9) are reported in Table 2. Column (1) reports results from an OLS regression of the log of groundwater extraction on the log of prices controlling for well fixed effects. Column (2) further controls for month fixed effects and column (3) controls for aggregate shocks by conditioning on basin-wide surface water consumption, drought, precipitation, squared precipitation, degree days, and SWP allocations. Column (4), which presents results from our preferred specification, further conditions on the annual quantity of water delivered for recharge in each region.

Table 2: Double-Log Fixed-Effects Regression

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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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</table>

Notes: Results are reported from a fixed-effects OLS model. The dependent variable is the natural log of groundwater extraction for well \( i \) in month \( t \). In parentheses are standard errors clustered at the well level, with *, **, *** denoting significance at the 10%, 5%, and 1% level. In brackets below are standard errors clustered at the region level. Aggregate shocks include basin-wide consumptive use of surface water, SWP allocation announcements, and weather controls (drought indices, precipitation, squared precipitation, and degree days). Column (5) limits the sample to wells in East Whitewater only, the region that is dominated by agricultural wells.

Our results highlight that volumetric groundwater prices impact groundwater use in a modest yet meaningful way, with price elasticity estimates ranging between -0.17 to -0.20 across the alternative specifications. In our preferred specification, we find that if the price of groundwater increases by 1%, we expect this to cause a 0.17% decrease in extraction. The price elasticity estimates are robust to the exclusion and inclusion of weather including drought indexes, surface...
water use, surface water supplies, and annual regional groundwater recharge.

One complication when interpreting these elasticity estimates is that well users in the CVWD are comprised of residential users, agricultural users and golf courses. To assess the extent to which this estimate reflects the price elasticity of demand for agricultural groundwater, we estimate equation (9) on a restricted sample of wells from the East Whitewater region only, since pumping in this area is almost exclusively agricultural. As shown in column (5) We find that demand is slightly but not significantly more responsive to price changes, with a demand elasticity of -0.22. The insensitivity of our results to this restriction lends confidence to the interpretation of the results reported in columns (1-4) as the short-run price elasticity for agricultural groundwater.

Our estimates of the price elasticity of demand for groundwater hinge on the assumption that aggregate annual shocks and intra-annual regional unobservables are not systematically correlated with prices and groundwater use. Results reported in Table 2 highlight that the price elasticity of demand for groundwater is insensitive to the inclusion of a number of potential confounding observables including annual monthly surface water use, weather, and the quantity of recharge supplied in a region-year.

Table 3 examines the sensitivity of our results to an array of observables that may bias our coefficient estimates. We begin by reproducing the results from column (4) of Table 2, our preferred specification, in column (1). Controls for annual total acreage in agriculture (col. 2), crop composition (col. 3), a linear time trend (col. 4), month-by-region recycled water deliveries (col. 5), and lagged prices (col. 6) do not alter our primary finding. In theory, changes in energy prices may confound the estimation since energy prices may be correlated with groundwater prices and affect groundwater extraction via pumping costs. In our setting, this does not pose an empirical concern. The Imperial Irrigation District supplies energy to all users, charges the same rate for all users, and importantly, did not change rates between 2000 and 2014. Our primary results are robust to an array of considerations, and we view this as

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4The sample size is restricted in (2) and (4) due to data limitations; land use data were only available for 2002-2015 and recycled water use data were only available from 2006-2015.
strong evidence in support of the plausibility of our main identifying assumption.

Table 3: Robustness to Alternative Specifications

<table>
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<td>Yes</td>
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Notes: Results are reported from a fixed-effects OLS model. The dependent variable is the natural log of groundwater extraction for well $i$ in month $t$. The baseline specification corresponds to the preferred specification of column 4 in Table 2. Each subsequent column reports an alternate specification: columns 2-6 control one-at-a-time for total irrigated acreage, crop composition, a linear time trend, recycled water use, and lagged prices. Column 7 reports estimates of the OLS regression in levels. Standard errors clustered at the well level are reported in parentheses, with *, **, *** denoting significance at the 10%, 5%, and 1% level. Standard errors clustered at the region level are reported below in brackets. Aggregate shocks include basin-wide, monthly consumptive use of surface water, annual SWP allocation announcements, and weather controls (drought, precipitation, squared precipitation, and degree days).

Lastly, we examine the sensitivity of our results to our modeling assumptions about the relationship between water use and volumetric prices. Column (7) of Table 3 presents results from the estimation of equation (9) where instead both groundwater extraction and groundwater prices are measured in levels. We continue to find that price increases lead to a significant reduction in agricultural groundwater demand, though demand is more elastic when prices and extraction are measured in levels. The coefficient estimate of -0.29 translates to a demand elasticity point estimate of -0.32, when evaluating at the mean values for extraction and prices.
7 Measuring the Gains from Trade

The creation of water markets that allow for water trading between agricultural and urban users poses an oft-discussed strategy to mitigate the costs of drought, and adapt to climate change. However, quantifying the efficiency gains from water trading has proven elusive. First, substantial administrative and legal costs are involved with water transactions across different political jurisdictions, and it is empirically challenging to account for these transaction costs in water trades (Ayres, Edwards, and Libecap 2017; Hagerty 2017; Regnacq, Dinar, and Hanak 2016). Second, real logistical and physical costs may be involved with the movement of physical water across distances, and current measures of the gains from trade are often gross as opposed to net of these costs. Third, it has been difficult to obtain micro-level evidence on the price elasticity of demand for agricultural water, and even more challenging to do so in an area where estimates of the urban price elasticity of demand also exist.

Our research setting allows us to overcome these administrative, logistical, and methodological obstacles. We focus on the gains from trade between the urban water users served by the City of Riverside and the agricultural users served by the Coachella Valley Water District. These entities are located in a single geographic and political jurisdiction, Riverside County, and rely on a shared aquifer as the primary water supply. For these reasons, transaction costs involved with coordinating transfers across political and administrative boundaries, and the physical costs involved with transporting water are minimal. Selling groundwater in this context is simply being paid to pump less. Another distinguishing feature of Riverside County is that we observe account-level panel data on agricultural water use in CVWD, and for residential water use in the City of Riverside. This allows us to construct parameters rooted in real-world observations about prices and consumption, and directly estimate the price elasticity of demand for residential and agricultural water.

\footnote{In the current draft, we use publicly available data on residential water use and mean monthly water use to construct measures of aggregate demand and average prices. We are still seeking approval from the City of Riverside to present results on residential price elasticity estimates. For this reason, we use results from Baerenklau, Schwabe, and Dinar (2014), who estimate a residential price elasticity from a different utility serving residential users in Riverside county.}
7.1 Parameters and Simulation

We begin by considering three scenarios: (1) business-as-usual where both sectors are unconstrained; (2) incomplete regulation where one sector faces a curtailment; and (3) complete regulation, which is defined by the efficient outcome that results from trade. Scenario 2, referred to as “incomplete regulation”, mirrors the 2015 drought mandate imposed by the California governor on residential water use throughout the state. This regulation required urban water consumers to reduce water use by 25% compared to 2013 quantities. We approximate this policy by imposing a 25% reduction on 2016 residential water use in the City of Riverside. In a final scenario, labeled “complete regulation”, we impose the same quantity restriction as in Scenario 2, but allow the reductions in water use to be achieved by either agricultural users in CVWD or urban users in the City of Riverside. We continue to assume that reductions in water use are imposed on urban users, but that urban users can now purchase (or sell) water from agricultural users.

To calculate the residential and consumer surplus under each of these scenarios, we implement the analytical framework set forth in Section 2.1, leaning exclusively on parameters that we either estimated or calculated using observations on urban and agricultural water use. Table 4 outlines the parameters needed to simulate the gains from water trade, including a description of the parameter, a symbol mapping it to the analytical framework, the parameter value, and the data source.

The slope of the demand curve for urban water, denoted $\sigma$, is informed by Baerenklau et al. (2014), who measure the price sensitivity of demand for residential water use in a part of Riverside County. Their demand estimates are relatively more elastic than other recent estimates of residential water demand in California and in North Carolina (Nataraj and Hanemann 2010, Wichman et al. 2016). To reflect the range of existing estimates on the price elasticity of demand, we will test the sensitivity of our results to a range of slope parameters. The slope of the agricultural water demand curve, denoted $\alpha$, is taken directly from column (7) of Table 3.

The quantity of urban water use permitted, or allocated, under the 25% drought mandate
Table 4: Parameter Estimates

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Estimate</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>Urban Demand Slope</td>
<td>$\sigma$</td>
<td>-.76</td>
<td>Baerenklau, Schwabe, Dinar (2014)</td>
</tr>
<tr>
<td>Agricultural Demand Slope</td>
<td>$\alpha$</td>
<td>-.29</td>
<td>Column (7) of Table 3</td>
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<td>Urban Coefficient</td>
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<td>Estimated with $(P,Q) = ($860/AF, 59055 AF)$</td>
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<td>Agricultural Coefficient</td>
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<td>Estimated with $(P,Q) = ($99/AF, 229981 AF)$</td>
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<td>Urban Allocation</td>
<td>$E_U = (1 - .z)x_U^*$</td>
<td>44,291 AF</td>
<td>75% of total urban consumption in 2016; observed with PUC data.</td>
</tr>
<tr>
<td>Agricultural Allocation</td>
<td>$E_A = x_A^*$</td>
<td>229,981 AF</td>
<td>Total pumped in 2016; observed with CVWD data.</td>
</tr>
<tr>
<td>Conservation Policy</td>
<td>$z$</td>
<td>25%</td>
<td>2015 Urban Drought Mandate</td>
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</table>

Notes: The table lists the relevant simulation parameters, parameter values, and source.

is denoted by $E_U$. To calculate this quantity, we obtained data on aggregate monthly water use for residential customers served by the City of Riverside, and summed this for all months in 2016. This quantity reflects $x_U^*$, the quantity of urban water consumed in the absence of the mandate. The urban allocation is equal to 75% of the quantity consumed in 2016, which is 44,291 AF. The reduction in water use required by the drought mandate is therefore 14,764 AF.

The quantity of water allocated to agricultural users is equal to the quantity of water consumed in the absence of regulation. Recall that our simulation mirrors the mandatory restriction imposed by the Governor, and this mandate excluded agricultural users. To calculate aggregate water use, we take the sum of groundwater extraction across all users in the CVWD in all months of 2016. Agricultural water use in 2016 totals 229,981 AF, or roughly 5-fold the consumption by urban water users.

The parameters labeled the agricultural and urban demand coefficients reflect the price at which agricultural and urban waters value the first acre-foot of water. Given our functional form assumption, this parameter for agricultural users, denoted by $\gamma_A$ is equal to $P + \alpha x_A$, 31
and is a function of price, the quantity of water demand, and the slope of the demand curve. We can estimate this parameter using our slope estimate and a point on the demand curve for agricultural groundwater.\(^6\)

We use a point on the demand curve that corresponds to the observed aggregate annual groundwater extraction in 2016 (or \(x_A^*\)) and the associated price per unit of groundwater. To calculate the price, we assume that the marginal price equals the average marginal pumping price in 2016, and is a combination of the volumetric charge and the energy cost to pump an acre-foot of water to the surface. The volumetric charge is a weighted average of three uniform volumetric prices charged in CVWD. To impute the average energy cost per acre foot of water we follow a well-known engineering formula presented by Rogers and Alam (2006), assuming an average depth to the water table of 152 feet, and the price per kWh of energy for agricultural users in 2016 of $.0618/kWh. We translate the depth and energy prices to an average per AF energy cost of extraction (Rogers and Alam 2006).\(^7\) The imputed price of groundwater is $99 per AF, and the quantity of agricultural groundwater consumption corresponding to this price is 229,981 AF. This generates an agricultural demand coefficient equal to $66,793.

In a similar fashion, we also calculate the corresponding urban demand coefficient using the slope of demand for urban water reported in Table II, the observed unconstrained aggregate quantity of residential water consumed in 2016, and the average marginal price corresponding to this quantity. To measure the average marginal price corresponding to \(x_U^*\), we first take advantage of observed data on average water use per household in each month of 2016. We match this with rate schedules that publish the tiered pricing structure in each season including the quantities of water that fall within each tier, the marginal price in each tier and the fixed cost. We then calculate in each month the average price per AF of water, and take a weighted average of this price across all months in the year. We measure an average price per acre-foot

\[^6\]The agricultural and urban demand coefficient estimates should not be interpreted literally, as they are characterized by large out-of-sample predictions.

\[^7\]The full per-unit price of an AF of groundwater in time \(t\) is given by \(P_t = \phi p^e_t h_t + P_{RAC,t}\), the sum of the energy extraction costs and the volumetric price, where \(P_{RAC}\) is the volumetric price of groundwater per AF, \(h_t\) represents the height of the water table, \(p^e_t\) is the energy price, and \(\phi\) is the energy requirement to raise an AF of water up one foot (Rogers and Alam, 2006).
of $860.53 or $1.98 when measured in ccf, a price that is almost identical to that reported by Baerenklau et al. (2014). Using this price and the unconstrained aggregate quantity of residential water consumed in 2016, $x_U^* = 59055$ AF, we arrive at a $\gamma_U$ estimate of $45,742$.

The set of parameters summarized in Table 4 fully characterize the analytical framework and enable us to apply the model to Riverside County.

7.2 Gains from Trade

Figure 10 illustrates the main results from our simulation, including the equilibrium price for traded water, the quantity of trade between urban and agricultural users, and the increase in surplus to urban and agricultural water users. The width of the horizontal axis denotes the quantity of water abatement required under the California drought mandate. Moving from left-to-right, the horizontal axis measures urban water abatement and moving from right-to-left, the axis denotes agricultural water abatement. This figure is drawn such that the 14,763 AF of abatement required under the drought mandate is achieved via any combination of abatement by urban and agricultural users. We assume that prior to trade urban users are required to abate all 14,763 AF. The lines denoted $D_U(x_U)$ and $D_A(x_A)$ depict the inverse demand curves for agricultural and urban water, assuming abatement ranging from 0 to 14,743 AF.

Our simulation suggests that agricultural users will sell 11,411 AF of water to urban users with an equilibrium price of $3,408. Framed differently, approximately 77% of the water conservation mandate will be achieved through a reduction in agricultural water use when voluntary trade is allowed. As shown in the areas shaded green and blue in Figure 10, the gains from trade relative to incomplete regulation amount to $68 million. We find that the welfare costs to residential users from compliance with the 25% mandatory reduction in water use could have been reduced by 60% or $49.5 million if water trading was permitted. As shown in Figure 10, agricultural users would also strictly benefit from the establishment of water markets. We estimate that agricultural surplus would increase by $18.8 million if water trading was permitted.
Our estimate of the gains from trade hinges on a number of important assumptions. These include the functional form of demand for agricultural groundwater, the functional form of the demand for urban groundwater, our measures of average marginal prices for agricultural and urban water, and our estimation of aggregate demand. Moving forward, our plan is to demonstrate the sensitivity of our gains estimate by showing how the magnitude changes as marginal prices, allocations, elasticities, and functional forms change. A separate caveat in the interpretation of our results is that we restrict our attention to the gains from trade between one urban municipal utility and one irrigation district. We anticipate that the gains might change if our sample was expanded to include the population of urban and agricultural users throughout the entire state.

8 Conclusion

In this paper, we determined the optimal water abatement for a given conservation policy and evaluated the role of markets as an adaptation strategy to climate change. After first establishing a simple analytical framework to characterize the costs of incomplete water regulation, we estimated the price elasticity of demand for agricultural water and simulated the efficiency gains from water trade across sectors. We utilized monthly, well-level panel data on agricultural groundwater extraction and prices to estimate an elasticity that is the first of its kind to not rely on estimates of pumping cost for price. Our results suggest that prices have a modest, yet significant effect on groundwater extraction, with elasticity estimates ranging between -0.17 to -0.22 across alternative specifications.

Our simulation highlights that water markets would have substantially lessened the welfare losses from compliance with California’s 2015 drought water conservation mandate. Results based on linear water demand curves suggest that the welfare impacts to residential users from the drought mandate could have been reduced by 60%, from $83 million to $33.5 million, with a well-functioning water market. Although our simulation depends on some simple structural
Figure 10: Gains from Complete Regulation

Notes: $D_A$ and $D_U$ denote inverse aggregate demand curves for agricultural and urban water, respectively. The total amount of required water abatement, $.25 x^*_U = 14,763$ AF, is fixed on the x-axis. Any point along the axis represents a different allocation of abatement between types. $x^+_U$ and $x^+_A$ represent the optimal abatement across sectors and $p^T$ denotes the market-clearing price in equilibrium. The benefits to urban users from complete regulation, i.e., the benefits to residential users from ag-urban water trade, are shown by the shaded triangle.
assumptions, all parameters were estimated with observed data from a single county, an area characterized by both a productive agricultural region and a populous urban area. Importantly, the demand slope parameters were estimated with micro-level data on both agricultural water use and urban water use.

This paper provides a critical first-step in considering the role that water markets might play in climate change adaptation. Climate change is expected to bring increased variability in precipitation, including more frequent and severe droughts. We introduce a framework with which to evaluate the gains from water trading conditional on any given reduction in use, enabling us to evaluate a range of climate change scenarios. We show that one strategy to reduce the costs of climate change is through the establishment of water markets, particularly in regions where legal and physical transaction costs are minimal.

References


