Missing Markets: Evidence on Agricultural Groundwater Demand From Volumetric Pricing*

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Abstract

Market-based instruments pose widely prescribed but rarely implemented tools to manage scarce water resources. We estimate the price elasticity of demand for agricultural groundwater in a water district with volumetric pricing and monthly well-level extraction data spanning 17 years. Demand is inelastic, with estimates ranging from -0.16 to -0.2. We apply this parameter to calculate the surplus change from the introduction of agricultural water pricing, and the prospective gains from water transfers between urban and agricultural users, with and without water supply curtailments. Relative to a water conservation mandate applied uniformly to all users, trading can substantially mitigate the costs of water scarcity.

JEL: D47; Q15; Q25; D61; R52
Keywords: environmental regulation; market-based approaches; groundwater; agriculture; climate change

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1 Introduction

Incomplete markets in the governance of water may lead to substantial allocative inefficiencies. A first inefficiency stems from distortions in the pricing and allocation of scarce water supplies across users (Burness and Quirk 1970; Vaux and Howitt 1984; Chong and Sunding 2006). Agricultural and urban users typically face different prices for water supplied from a shared source, and existing regulations and institutions often make water trading economically infeasible (Archibald and Renwick 1998; Garrick et al. 2013). A second inefficiency is specific to groundwater and arises because traditionally this open-access resource has been unregulated (Provencher and Burt 1993). This has led to declining water tables, compromised water quality, increased pumping costs, and questions about the availability of future water supplies.

Market-based instruments may offer a cost-effective approach to regulate groundwater and remedy existing distortions (Tietenberg 1980; Baumol and Oates 1988; Goulder and Parry 2008). In a number of settings, including local and global air pollution and fisheries, market-based instruments have been implemented to manage the environment, and shown to do so at a lower cost than more prescriptive approaches (Carlson et al. 2000; Keohane 2006; Costello et al. 2008; Fowlie et al. 2012, Cicala 2020). Contrast this with the water setting, where our experience with and empirical understanding of prices and cap-and-trade are more limited. While volumetric water pricing is the norm in the residential setting, it is relatively absent in the management of agricultural water, which accounts for over 80% of consumptive water in the Western U.S.[1]

With limited direct empirical evidence on demand for agricultural groundwater, it is challenging to foresee how agriculture will respond to a groundwater tax or a cap on groundwater extraction (Grafton et al. 2012; Leonard et al. 2019). However, to date obtaining these estimates has proven elusive. A first obstacle to estimating demand is the dearth of data on agricultural water use at a temporal and cross-sectional resolution necessary for credible estimation. Where these data do exist, a second obstacle arises

[1]Water pricing in the residential setting has been the focus of a rich literature (Nataraj and Hanemann 2010; Olmstead 2010; Baerenklau et al. 2014; Wichman et al. 2016). A smaller yet growing empirical literature exists on surface water transfers between agricultural and urban users or among agricultural users (Wheeler et al. 2008; Donna and Espín-Sánchez 2018).

due to the absence of prices for water. For this reason, existing estimates on the price elasticity of agricultural water demand rely on aggregate measures of water or proxies for water prices.[2] Given the magnitude of the agricultural sector, water management policies that seek to mitigate existing market failures or the costs of climate change must incorporate it.

In this paper, we overcome these hurdles by estimating the price elasticity of demand for groundwater in a setting that features volumetric prices for agricultural groundwater pumping. Our empirical approach takes advantage of monthly, well-level data on groundwater extraction spanning 17 years in a jurisdiction that employs three geographically based pricing regimes for groundwater. Our estimates offer direct evidence on pricing, one type of market-based approach, as a tool to manage groundwater in practice. We then apply our estimated price elasticity to compute the surplus change from the introduction of agricultural water pricing. However, this price may not be efficient, as distortions remain between the prices charged to agricultural and urban users for water drawn from the same source.[3] We simulate the surplus gains from a second market-based approach, trading between urban and agricultural users, in the presence and absence of water supply curtailments. These applications illustrate the importance of the agricultural elasticity parameter when measuring the prospective change in surplus from groundwater pricing and transfers.

We use well-level data on groundwater extraction to estimate the price elasticity of demand for irrigated groundwater in the Coachella Valley, a productive agricultural region in California. Three features of this empirical setting give rise to a research design that allows for estimation of the short-run price elasticity of demand. First, this water district charges all agricultural well users a volumetric rate for groundwater extraction, so water prices and water use are directly observed. Second, three distinct geographically based pricing regimes exist within a single water district, and these prices change over time.

[2]Previous studies lean on energy prices and groundwater depth to measure extraction costs (Gonzalez-Alvarez et al. 2006; Hendricks and Peterson 2012; Burlig et al. 2020), self-imposed taxes (Smith et al. 2017), or aggregate measures of water use (Graveline and Mérel 2014).

[3]Market-based approaches are defined as a price or a quantity instrument in which the price on groundwater (or a cap on groundwater extraction) is set by a regulator and the market determines the quantity (or the price in the case of a tradeable quantity instrument) (Baumol and Oates 1988; Goulder and Parry 2008). The price or cap chosen by the regulator may not be efficient.

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. This assignment mechanism allows for direct estimation of the relationship between volumetric water prices and agricultural water demand.

A key empirical result is that demand for agricultural groundwater, net energy costs, exhibits a relatively inelastic response to water prices in the short run. Controlling for fixed well unobservables and aggregate seasonal shocks, we estimate a monthly price elasticity of -0.17. This result is insensitive to the inclusion of regional time-varying observables such as surface water use that might be systematically correlated with both groundwater extraction and regional prices.[4] To test the robustness of our elasticity estimate to unobservable basin-wide shocks, we use a difference-in-differences framework to evaluate the effect of the introduction of groundwater pricing in one region on extraction. We report an elasticity of -0.15, which suggests that our main estimates are not driven by aggregate shocks.

Well-identified estimates of the price elasticity of demand for agricultural groundwater are essential to understand the costs of impending groundwater regulations and changing water supplies projected over a range of climate models. In California, models indicate that climate change will increase inter-annual variability in precipitation, and the extremity and frequency of droughts (Swain et al. 2018). Groundwater constitutes 40% of California's water supply on average, but even more during droughts when it serves as a buffer against negative shocks. The long-run availability of groundwater to mitigate the costs of drought and smooth consumption depends on its management (Gemma and Tsur 2007). Currently, states are developing groundwater regulations that monitor and cap groundwater use. This includes California's Sustainable Groundwater Management Act of 2014 (SGMA), which requires groundwater basins to design and implement plans to achieve sustainable groundwater levels. Notably, this regulation gives water districts flexibility in how they manage groundwater. Groundwater pricing may operate to manage groundwater and surface water jointly as a climate change adaptation strategy, or as an

[4] A separate consideration relates to the external validity of the our estimate. The drawback of a single-basin study is that our estimates may not generalize to other groundwater basins. However, the appeal is that a basin will define a groundwater market, since California law regulates groundwater at the basin-level (Bruno and Sexton 2020).

instrument to comply with SGMA. Our work provides some of the first empirical evidence on the impact of a groundwater price as a tool to manage groundwater use.

The Coachella Valley, CA is endowed with a number of properties that make it a favorable setting in which to simulate the surplus change from the introduction of (i) agricultural water pricing, and (ii) groundwater trading between agricultural and urban users. From a policy perspective, it is home to a productive agricultural region with volumetric water pricing and a large urban population that experienced a conservation mandate during the last drought. From a research design perspective, our focus on the gains from trade in a single geographic and political jurisdiction where all users draw from the same aquifer overcomes the well-known difficulty of disentangling efficiency gains from transaction costs (Regnacq et al. 2016; Ayres et al. 2018; Hagerty 2019).[5] A final advantage of our setting is that all estimates and calculations are generated from observational data in Riverside County. Despite these features, our trading simulation is limited in that it imposes structural assumptions on residential and agricultural demand for water and models a hypothetical market.

Our simulation highlights sizable changes in surplus from agricultural groundwater pricing and groundwater trading across user types. We calculate a $10.7 million change in surplus, which amounts to roughly 45% of the market size for agricultural groundwater, from the introduction of a volumetric charge for agriculture. Even with agricultural groundwater pricing, price differences between agricultural and urban users remain and impose costs amounting to $1.25 million or roughly 3.3% of annual groundwater expenditures. Water transfers pose one option to reduce these costs. Trade could also mitigate the economic costs from mandatory curtailments to water supplies. In response to the 2015 drought, urban users in California faced a 25% mandatory reduction in water use. In the CVWD, water trading could have reduced the cost to comply with the mandate by 43%. We continue to simulate gains from trade when we introduce water curtailments that are applied uniformly across both sectors. Under mandatory curtailments of up to

[5] Our simulation makes assumptions about the assignment of water rights across urban and agricultural users. A related literature considers the economic value of well-defined property rights for water, finding that agricultural output and land values increase substantially in their presence (Ayres et al. 2018; Ayres et al. 2020; Browne 2018). Clear, enforceable and well-established property rights are critical to the establishment of well-functioning water markets (Coase 1960; Hornbeck 2010).

20%, transfers could reduce annual compliance costs by 35 to 44%. These results imply that markets could play an important role in reducing the costs of water scarcity.

For two reasons our simulated results on hypothetical trading are informative for the design and development of water markets. First, our simulation imposes parameter values on agricultural and urban water use, and a critical question is how the gains from trade vary as a function of these values. A sensitivity analysis reveals that the magnitude of the gains from trade is most responsive to the agricultural elasticity parameter. This underscores the importance of credible estimation of this parameter. Second, we simulate substantial gains from trade even under conservative assumptions. Modifying our elasticity estimate to include energy extraction costs or applying this parameter to the typical agricultural setting where groundwater is unpriced increases the gains from trade. Our lower-bound measure suggests that in other California groundwater basins where agricultural water is unpriced, trading may lead to meaningful welfare gains. Lastly, we view our price elasticity estimate as a valuable input in or comparison point to a recent literature that uses quasi-experimental approaches and simulations to weigh in on the gains from water trading (Edwards et al. 2018, Donna and Espín-Sánchez 2018; Hagerty 2019; Bruno and Sexton 2020; Rafey 2020; Ayres et al. 2020).

2 Background

The Coachella Valley Water District (CVWD), located in Riverside County, California and identified on a map in Figure 1, provides an ideal setting in which to estimate the price elasticity of demand for agricultural groundwater and simulate the surplus change from the introduction of market-based instruments. It supplies domestic water to five cities that serve roughly 285,000 urban customers. Domestic users rely exclusively on water provided from the Coachella Valley groundwater basin as their drinking water source.[6] This water district is also home to a productive agricultural region, with roughly 60,000

[6]To transport groundwater from the aquifer to the household, the district pumps groundwater to one of 58 distribution reservoirs and then delivers this water to households via distribution piping. According to CVWD's 2016 residential rate study, treatment and transmission constitute 7% and 11% of the operations and maintenance budget, respectively (CVWD 2016b). This suggests that treatment costs comprise a relatively small portion of the variable costs to supply drinking water.

acres in crop production and over half a billion dollars in crop revenue. Agricultural users in our study area draw water from the same aquifer. For this reason, a water market overlying the Coachella Valley Groundwater Basin could occur by simply trading the rights to pump groundwater.

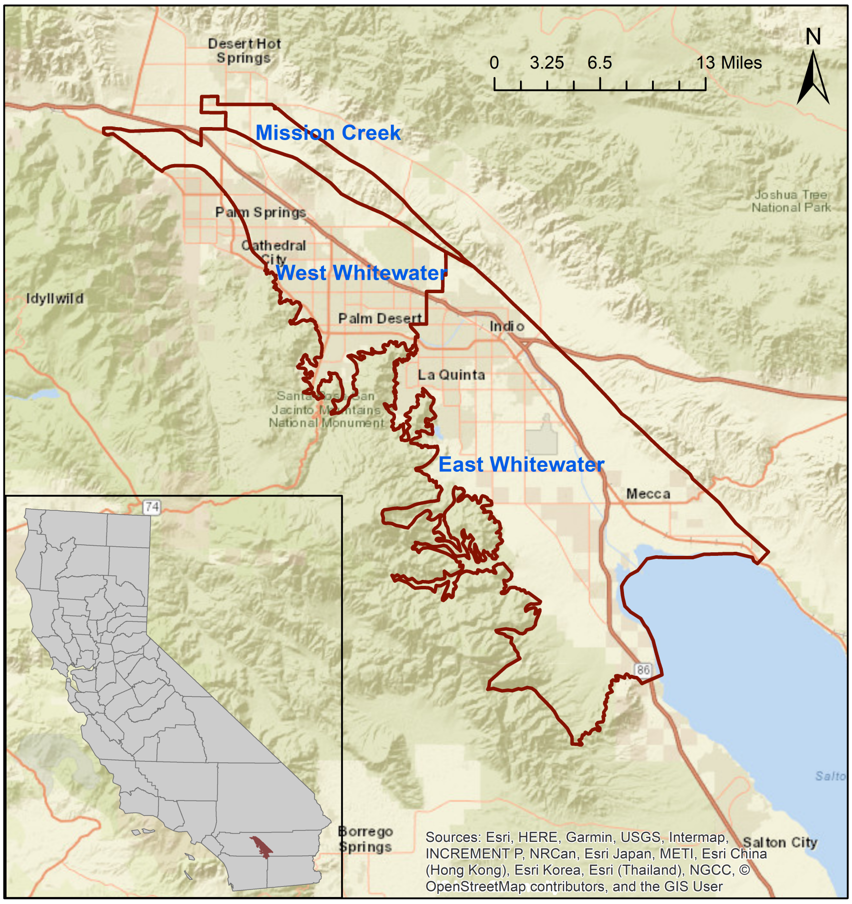
2.1 Replenishment Assessment Charge

A unique feature of the CVWD is that it charges agricultural users volumetric prices to pump groundwater, and deploys three location-specific rates. Figure 1 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 (AF) for groundwater extraction, called the Replenishment Assessment Charge (RAC) that is determined by the agency. This groundwater pricing scheme stands in contrast to the pricing structure implemented across most of the U.S. Most agricultural users that rely on groundwater for irrigation do not face a price beyond the energy costs incurred to lift the groundwater from the water table to the surface. In the CVWD, the RAC is large relative to energy extraction costs, comprising roughly 85% of the full price of groundwater.

Groundwater overdraft in the CVWD and the need to acquire new supplies led to the introduction of the RAC. Beginning in 2004, a charge was imposed on all users extracting more than 25 acre-feet per year. The revenue collected from these tariffs funds the artificial replenishment of the underlying aquifer using surface water imports. The cost to recharge the aquifer includes the capital costs to construct replenishment facilities used for recharge, the costs to operate and maintain these facilities, and the costs to import water from the State Water Project and the Colorado River for recharge. The RAC reflects these costs of service, and adjusts over time to account for alternative non-potable water supplies, changes in the costs to import water, and changes in operation and maintenance costs.

One complication with water fees and assessments in California is that water users can only be held legally responsible for their share of costs associated with a project, a result of California's Proposition 218. This proposition requires that the taxes charged to different parcels reflect the proportionate service that land parcels receive in return. This

Figure 1: Coachella Valley Water District Service Area



Notes: This figure illustrates the location and boundaries of CVWD's service area. The three regions, East Whitewater, West Whitewater, and Mission Creek, face different prices for pumping groundwater.

likely explains why three geographically distinct volumetric prices were established in a single water district. As discussed in Section 4.1, both the benefits and costs of recharge differ across the three regions.

2.2 Agriculture and Water Use in the CVWD

Agriculture in the Coachella Valley, like much of California, is comprised of a relatively high density of high-value perennial crops. The area is known for its production of dates, as well as table grapes, citrus fruits, bell peppers, and other vegetables. In the CVWD, perennial or permanent crop production accounts for 36 to 56% of annual acreage, and a diversity of high-value vegetables and nursery crops make up roughly 40 to 60% of annual crop acreage. Field crops such as grain and alfalfa amount to less than 5% of acreage in a given year. Crop composition in the Coachella Valley and in California looks systematically different from agriculture in the Midwestern U.S., where over 75% of acreage is planted with annual field crops. Given these differences, it is unlikely that recent estimates on the price elasticity of demand for agricultural groundwater derived in the Midwest will apply to California.

Agriculture depends heavily on groundwater and Colorado River water for irrigation. On average, groundwater accounts for 1/3 to 1/2 of the total water supply. Surface water, which supplies between 1/2 to 2/3 of the agricultural water supply, is delivered from the Colorado River and transported to agricultural customers through the Coachella Canal.[7] All agricultural pumpers pay the same volumetric canal rate for surface water. These rates do change over time, in response to changes in the cost of service. A unique feature of our setting is that surface water prices and supplies may influence groundwater prices. This is because surface water supplies are used to artificially replenish the aquifer. We discuss the empirical challenges posed by surface water supplies, detail how our empirical approach accounts for the possibility that surface water rates and deliveries may confound estimation, and provide additional institutional background on surface water supplies in Section 5.2 and Appendix A.

2.3 Water Policy and Agricultural Water Use in California

Almost all agriculture in California is irrigated, and over half of farms in the state rely on a mix of surface and groundwater sources for irrigation. In an average year, groundwater supplies about 40% of water consumed. While substantial heterogeneity exists in the ratio of surface to groundwater supplies across districts, the relative proportion of groundwater and surface water in the CVWD looks similar to the state's average consumption profile. There is also substantial interannual variability in groundwater use, with groundwater accounting for up to 80% percent of supplies during droughts. One reason for the increased reliance on groundwater during droughts is that historically groundwater use has been

[7] The base allotment of water from the Colorado River is set at 330,000 AF per year and due to the relative seniority of the district's water rights, surface water deliveries exhibit little inter-annual variation.

largely unmonitored and unregulated at the state level.

In response to increased concern over declining groundwater tables, the state passed the Sustainable Groundwater Management Act (SGMA) in 2014. This historic regulation represents California's first formal attempt to regulate and monitor groundwater use, and requires groundwater basins to develop and implement plans to achieve and maintain sustainable groundwater levels over the next two decades. Importantly, the authority for the design and deployment of this regulation is occurring at the local level. More than 250 Groundwater Sustainability Agencies have formed in over 140 groundwater subbasins, where these agencies are tasked with achieving groundwater sustainability in their jurisdictions.[8] This level of regulatory authority suggests that groundwater policies, such as a price instrument or the establishment of a groundwater market, will occur at the basin level. This motivates our focus on the estimation of the price elasticity and the simulation of market performance in a single groundwater basin.

3 Data and Descriptive Statistics

Monthly well-level data on agricultural groundwater extraction and regional information on volumetric groundwater prices serve as the primary data to estimate the price elasticity of demand for agricultural groundwater. These are supplemented by data on weather, land use, surface water deliveries and prices, and quantities of artificial groundwater recharge. Table 1 provides descriptive statistics.

For the years spanning 2000 to 2016, the CVWD provided monthly groundwater extraction for all 900 wells subject to volumetric pricing. To preserve the anonymity of these wells, the utility removed all information on the location, geography and type of well, with the exception of the RAC region in which the well resided. The well-level groundwater extraction data form an unbalanced panel, where the imbalance reflects the addition of new wells over time. Groundwater users in our data span agricultural, urban and recreational users. In 2005, the agricultural, urban and golf sectors accounted for

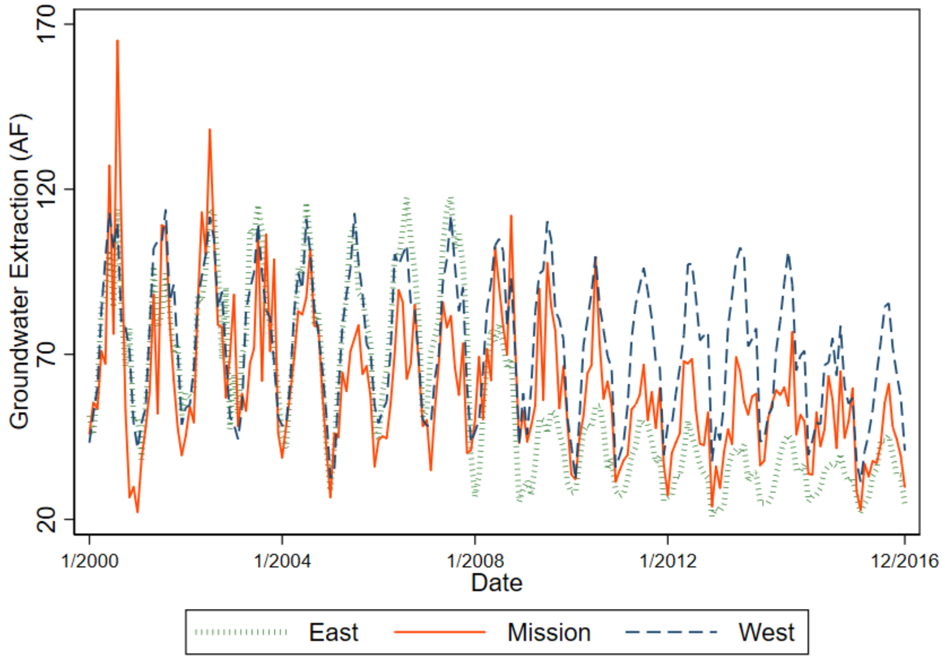
[8]The California Department of Water Resources delineated California's aquifer systems into a set of subbasins. Geology and hydrology primarily determine basin boundaries, but some basins were further divided by political boundaries such as county lines.

Table 1: Descriptive Statistics

	Obs	Unit of Obs	Mean	SD	Min	Max
Water Use and Water Prices						
Groundwater Extraction (AF)	66,445	Well-Month	57.24	67.75	0.00	537.10
Price (Groundwater) ($/AF)	612	Region-Month	64.76	33.98	0.00	128.80
Canal Rates (Surface) ($/AF)	204	Month	27.84	7.17	14.50	33.95
Recycled Deliveries (1,000 AF)	264	Region-Month	0.35	0.42	0.00	1.72
Recharge (100,000 AF)	46	Region-Year	0.54	0.70	0.00	2.57
Surface Water Use (100,000 AF)	204	Month	0.27	0.07	0.08	0.40
State Water Project Deliveries (%)	17	Year	0.54	0.27	0.05	1.00
Weather						
Precipitation (Inches)	204	Month	0.19	0.25	0.00	1.76
Max Avg Daily Temp (F)	204	Month	89.40	13.23	67.84	111.29
Min Avg Daily Temp (F)	204	Month	61.42	13.09	40.68	84.71
Growing Degree Days	204	Month	625.11	124.9	338.24	744
Harmful Degree Days	204	Month	419.01	445.95	0.00	1117.5
Drought Index 0	204	Month	17.53	22.70	0.00	97.94
Drought Index 1	204	Month	23.34	25.31	0.00	100.00
Drought Index 2	204	Month	22.94	27.34	0.00	100.00
Drought Index 3	204	Month	10.27	21.50	0.00	100.00
Drought Index 4	204	Month	0.07	0.13	0.00	0.41
Agriculture and Crops (Acres)						
Total Area Irrigated	14	Year	54,837	3,693	43,613	59,626
Citrus	14	Year	8,414	900	7,154	10,714
Tree, Vine	14	Year	14,989	887	13,663	16,213
Vegetable, Melon, Misc.	14	Year	25,700	3,635	15,085	30,296
Field, Seed	14	Year	2,239	533	649	2,763
Nursery	14	Year	3,502	667.64	2,533	5,043

Notes: This table reports the number and unit of observations, means, and standard deviations for well-month, region-month, region-year, year and month observables. The drought indices measure the percentage of land in Riverside County experiencing different degrees of dryness from Drought Index 0 representing "abnormally dry" conditions to Drought Index 4 representing "exceptional drought" conditions. Water is measured in acre-feet (AF). Land use data were only available for 2002-2015 and recycled water use data were only available from 2006-2015.

Figure 2: Average Monthly Groundwater Extraction by Region



Notes: The figure plots average monthly groundwater extraction per well in each region.

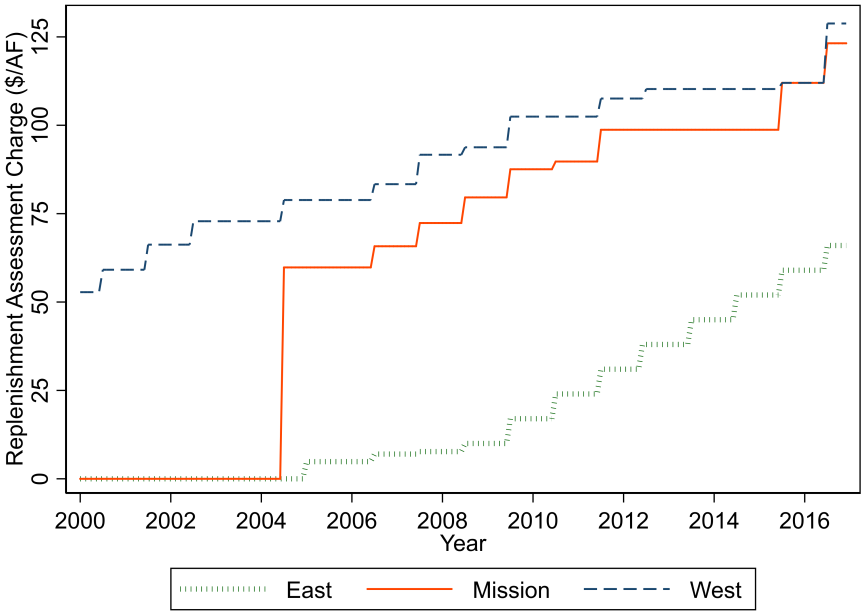
45%, 33% and 17% of water use, respectively (CVWD, 2012).[9] While we cannot precisely segregate agricultural wells from other well types, we are able to approximate the locations where farming occurs, and assess the robustness of our results to this sample.

Figure 2, which plots average well-level monthly groundwater use for each region over time, shows the temporal and cross-sectional variation in groundwater use. We observe strong seasonal patterns, with extraction peaking in the hot, dry summer and reaching a trough in the dormant month of January. A visual inspection also reveals meaningful differences in the levels of and changes in water use across regions. Groundwater extraction declines dramatically over time in the East and Mission Creek regions and remains relatively unchanged in the West. Differences in extraction may occur because of differences in land use, prices, or the availability of surface water.

Figure 3 plots the monthly RAC or volumetric price charged per AF of groundwater extracted in each region. All customers within a region face a uniform price. Price

[9]Wells serving urban customers are owned and operated by the water district. Water from these wells is distributed via a pipe network to households and priced according to the residential tariff schedule.

Figure 3: Volumetric Groundwater Prices by Region



Notes: The figure plots monthly volumetric groundwater prices by region.

changes may occur annually, and take effect in the same month - July - across all regions. This figure 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 in fiscal year 1980-81 in the West, in July 2004 in Mission Creek and in January 2005 in East Whitewater. Due to the staggered introduction of prices, we observe well-level groundwater use for two districts during months when volumetric prices are zero. Second, volumetric rates across all three regions follow a clear increasing trend, and there are regional differences in prices and price changes. The East and Mission regions experience the largest price changes over the panel. Third, a comparison across Figures 2 and 3 suggest no obvious patterns between prices and groundwater extraction– the highest quantities of extraction and prices are observed in the West, and the lowest extraction quantities lowest prices occur in the East.

To account for the possibility that groundwater extraction and prices may be correlated with surface or recycled water supplies, surface water prices, groundwater recharge, or land use, we obtained monthly or annual data on these variables. As shown in Table

1, recycled water deliveries and the quantity of groundwater recharge vary at the region-year level. This information was reported in documents published by the water district (CVWD 2016a). Monthly data on district-level agricultural surface water prices and surface water use were obtained from CVWD and the U.S. Department of Interior. We also collected information on surface water deliveries to the state in a given year via the State Water Project, since annual deliveries may influence the amount of water available for groundwater replenishment.[10] Lastly, annual land use and crop production data were collected from Riverside County's Agricultural Commissioner's Office Annual Crop Reports, which describe total irrigated acreage in various crop categories (ACO 2015).

We also collected data on drought and aggregate weather shocks to address the possibility that precipitation may affect groundwater extraction and trend with prices over time. Daily precipitation and temperature data were collected from the Indio Fire Station weather station in Riverside County. Daily precipitation was summed to measure total monthly rainfall. Growing degree day and harmful degree day variables, our measures of temperature, were constructed from daily average temperatures (Richie and NeSmith 1991; Schlenker et al. 2007). 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).[11]

4 Empirical Framework

The deployment of three different volumetric pricing regimes for groundwater extraction within a single water district provides an opportunity to improve on previous approaches used to 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

[10] The California Department of Water Resource's State Water Project announces allocations, which range from 0-100% of the quantities requested in State Water Project surface water contracts.

[11] 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."

of the main identifying assumptions, and present our econometric specification.

4.1 Research Design

Credible estimation of the impact of volumetric tariffs on groundwater extraction relies on the assumptions that assignment to a pricing regime and changes in groundwater prices over time are independent of potential outcomes. We now discuss the process by which wells were assigned to a RAC region, and provide empirical evidence to suggest that this assignment mechanism is independent of baseline groundwater use. We then describe the determinants of prices and price changes, including potential confounding factors.

4.1.1 Assignment of Wells to a Region

The underlying hydrology in the CVWD determined the boundaries of the three unique groundwater pricing regions. This delineation was based on California law that requires volumetric fees to reflect the benefits rate payers receive from the groundwater replenishment program. 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 hydrologic features, such as pressure or aquifer depth, that influence groundwater recharge. The concern surrounding this assignment mechanism is that assignment of a well to a region may be systematically related to water use and the cost of groundwater extraction. As an example, the fixed depth to the aquifer may differ across two regions.[12] All else equal, a shallower aquifer implies lower pumping costs, and pumping costs likely impact extraction quantities. Our empirical approach directly accounts for the possibility that fixed systematic differences may exist across pricing regimes through the inclusion of well fixed effects.

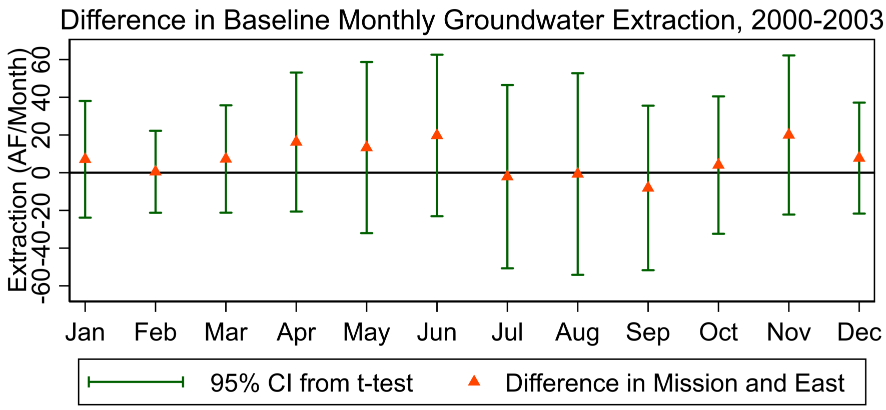
Still, we provide empirical evidence to support the assumption that the assignment of wells to a region is independent of potential outcomes. To do this we compare average monthly baseline water use, defined as the 48 months spanning January 2000 to December

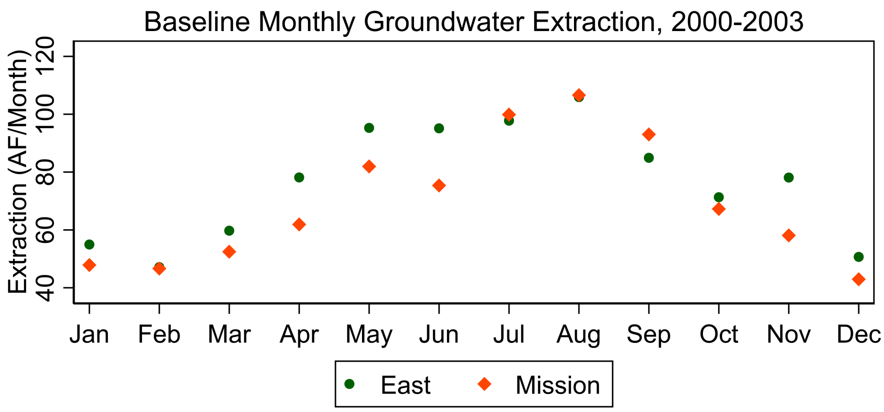
[12] An aquifer describes the subsurface layer that holds water, and the depth to the aquifer describes the depth to this layer. The water table describes the water held in this aquifer, and the depth to water table refers to the depth to access this water. In this simplified characterization, the depth to the aquifer is fixed while the depth to the water table varies over time.

2003, across regions. We begin with a comparison of mean groundwater use across the Mission Creek and the East regions, since these two regions faced a volumetric price of zero during this time period. Figure 4 illustrates mean monthly regional water use and the difference in extraction across the two regions, as well as the 95% confidence intervals. As shown in the lower panel, average groundwater use ranges from 47 AF to 105 AF in the East and from 47 AF to 100 AF in Mission Creek, with water use in both regions peaking in August. Substantial heterogeneity exists across wells in a month - the standard deviation in August water use in the East and Mission regions amounts to 100 and 65 AF respectively. The upper panel shows no significant differences in average monthly groundwater use across regions. Both in absolute and relative terms, differences across these two regions peak in November, with East wells consuming 20 AF or roughly 0.25 of a standard deviation more than Mission Creek wells.

Figure 5 compares average monthly groundwater use across the West and East regions for the same time period. The wells from these two regions comprise roughly 98% of our sample. The lower panel depicts average monthly water use by region, and illustrates that mean water use in the West ranges between 46.6 AF (standard deviation of 54 AF) in January and 106 AF (standard deviation of 84 AF) in August. Relative to the East, mean water extraction in the West is lower in the winter months, higher in some summer months, and similar in many months. A comparison of mean water use across the regions reveals that raw monthly water use is similar, with differences ranging from 0 to 0.17 of the standard deviation in monthly West water use. One complication with this comparison is that wells in the West faced a positive price during this time period. To account for this, we regress the level of water use on price levels in each month, and plot out the difference in mean monthly residual water use across the two regions, as well as the 95% confidence intervals. We find that monthly differences in water use increase conditional on the RAC. Residual water use is balanced across the two regions in most months, though a few differences exist. In January, average East groundwater extraction 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 4 and 5 suggest that in the years 2000-2003 assignment of

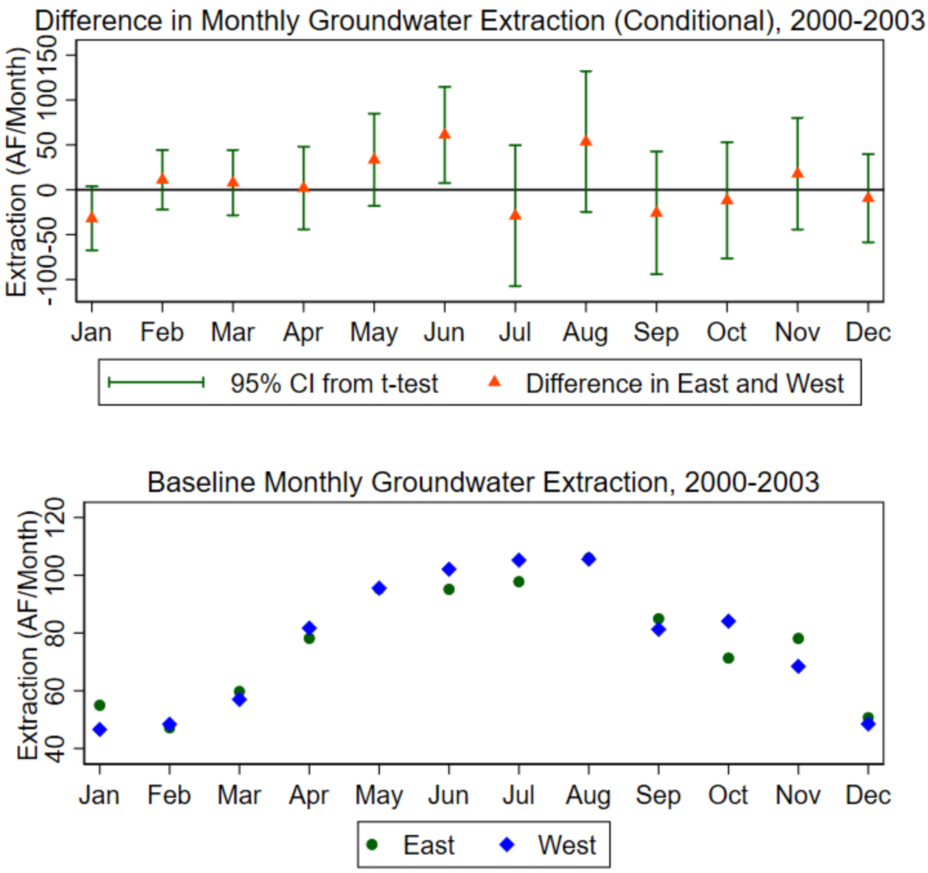
Figure 4: Monthly Water Use between East and Mission Creek Prior to Volumetric Pricing





Notes: The upper panel plots the difference in mean monthly groundwater use between East Whitewater and Mission Creek in the years, 2000-2003. Neither region faced a volumetric price for groundwater during this period. The vertical lines denote 95% confidence intervals. The lower panel plots mean monthly baseline groundwater extraction by region over the 4 pre-treatment years.

Figure 5: Monthly Water Use between East and West



Notes: The upper panel plots the difference in mean residual water use between the East and West Whitewater in the years 2000-2003. Monthly residuals are obtained from a regression of the level of water use on prices in each month. The vertical lines denote 95% confidence intervals. The lower panel plots mean monthly groundwater extraction by region between 2000-2003.

wells to regions is unrelated to baseline water use.

4.1.2 Determination of Prices

Regional differences in RAC levels and changes over time occur primarily because of cost differences associated with artificial recharge of the aquifer. The main drivers of differences in costs are the source and quantity of surface water used for groundwater recharge, the replenishment facility used for recharge, and the expansion of alternative non-potable water supplies. We condition on artificial recharge quantities in each region-year to account for the possibility that the quantity of surface water used for recharge may be systematically related to groundwater extraction and prices. This would occur if, for example, recharge quantities impact the depth to the water table, and hence gross groundwater prices. Our empirical approach also accounts for region-by-year recycled water deliveries since non-potable water deliveries may be correlated with the RAC, and impact groundwater extraction.

The source of surface water for recharge may bias our estimate of the price elasticity because it is a determinant of both groundwater prices and surface water prices.[13] The East region obtains surface water for replenishment directly from the Colorado River through CVWD's Colorado River allocation. In contrast, the Mission and West regions receive Colorado River water via the district's State Water Project (SWP) contract and an arrangement with the Metropolitan Water District, and this source is more costly. Because of the relationship between the source of surface water and both groundwater and surface water prices, surface water prices are positively correlated with groundwater prices. This implies that the price of surface water serves two roles: it reflects the price of a substitute good and may serve as a proxy for groundwater prices. If the former relationship dominates, then an increase in surface water prices will increase groundwater use; however, if the latter dominates then a price increase will decrease groundwater use. The empirical concern posed by surface water prices is that failure to account for them may bias our estimates of the price elasticity of demand for groundwater, but simply

[13] As an example, the Mission Creek region incurred reduced surface water deliveries during the 2014 California drought. This likely impacted groundwater extraction. As documented in CVWD (2016a), it was also partly responsible for an increase in the RAC.

conditioning on prices may confound estimation. For robustness, we estimate the price elasticity of demand with and without controls for surface water prices and water use.

4.2 Estimation and Identification

To estimate the price elasticity of demand for groundwater irrigation, we use well-level panel data and begin by estimating a simple fixed effects model using OLS,

$$w_{it} = \gamma_i + \beta P_{st} + \delta_t + \epsilon_{it}. \quad (1)$$

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 in region s and month t. To account for the possibility that fixed regional and well unobservables may be systematically correlated with both prices and groundwater use, our specification conditions on well fixed effects, γ_i. Month-of-year fixed effects, denoted by δ_t, are included to account for strong seasonal patterns in groundwater extraction. We compute standard errors that are robust to contemporaneous correlation within a region-year and serial correlation within a well over time (Cameron et al. 2011).

Of importance is the omission of year fixed effects from this regression. In our setting, prices change annually and in the same month for each region. While there exists some year-to-year variation in prices across regions, the inclusion of year or month-year fixed effects explains much of the variation. We are concerned that identifying variation remaining after the inclusion of these time controls is insufficient to learn about the relationship between prices and groundwater demand. However, the exclusion of these controls may also pose an empirical concern because month-of-year fixed effects do not capture aggregate annual or regional time-varying confounders. For the coefficient of interest β 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 and regional shocks such as droughts, surface water prices, and groundwater replenishment may be systematically correlated with both prices and groundwater use. To address concerns about potential omitted variables bias, we proceed in two directions:

a regression conditioning approach and a difference-in-differences model.

4.2.1 Regression Conditioning Approach

First, we augment equation (1) to explicitly condition on aggregate and regional time-varying observables (X) that may be systematically correlated with both prices and extraction,

$$w_{it} = \gamma_i + \beta P_{st} + \omega X_{st} + \rho X_t + \delta_t + \epsilon_{it}. \tag{2}$$

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 monthly observables, including precipitation, the drought index, temperature, surface water use, and 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. Aggregate surface water use and state water deliveries may 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 artificial recharge, the price of substitute goods, weather, and other time-invariant well characteristics. It rests on the assumption that, conditional on well and month fixed effects, and a rich set of aggregate and regional time-varying observables, time-varying unobservables that impact extraction are not correlated with prices. Explicitly, we assume that regional or district-wide time-varying shocks, such as investments in alternative water supplies or new and modified regulations and institutions that may influence agricultural water use, are uncorrelated with changes to the RAC. Though we cannot demonstrate that our identifying assumption holds, we offer two strategies to examine its plausibility. First, we test the sensitivity of our elasticity estimates 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 use, 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 other potential confounding factors, including changes in land use, lagged groundwater prices, surface water prices, flexible region time trends, and the monthly quantity of recycled water delivered to each region. Our motivation for conditioning on surface water prices is that they are positively correlated with regional groundwater prices, and will likely impact groundwater demand through the channel of surface water. 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 or recharge, and that the CVWD may use volumetric groundwater prices as a way to fund recycled water deliveries.

4.2.2 Difference-in-Differences Model

Second, our empirical setting also lends itself to a difference-in-differences framework in which we look at the effect of the introduction of volumetric pricing for groundwater on monthly groundwater use. This approach allows us to condition on year fixed effects, and examine if underlying aggregate annual shocks bias our price elasticity estimates. In the East region, we observe monthly groundwater extraction (between January 2000 and December 2003) when the volumetric price for groundwater extraction was zero, as well as monthly groundwater use after the introduction of a uniform volumetric rate of \$36.50 per AF on average for groundwater. In contrast, the West region charged a positive price ranging from \$53 to \$72 per AF during the "pre-treatment" period spanning January 2000 to December 2003. We take advantage of the introduction of volumetric rates in the East, and compare the change in water use in this region before and after the introduction of volumetric rates to changes in water use in the West across these two time periods. We implement this using a simple fixed effects model,

$$w_{it} = \gamma_i + \alpha Post_t + \beta East_i * Post_t + \omega X_{st} + \rho X_t + \delta_t + \epsilon_{it}. \tag{3}$$

The dependent variable, w_{it}, is groundwater extraction for well i in month t. The indicator variable $Post_t$ is set equal to 1 after the introduction of volumetric pricing in all regions, and zero otherwise. The variable $East_i$ denotes an indicator variable that is set equal to 1 if a well is located in the East region, and zero otherwise. It is interacted with $Post_t$ to indicate when volumetric pricing began for wells located in the East region. As before, we condition on well fixed effects, γ_i, where the variable $East_i$ is subsumed in the well fixed effect, and aggregate (X_t) and regional (X_{st}) time-varying observables. Importantly, since our model focuses exclusively on a policy change that was experienced by some users but not others, we can separate out this permanent pricing event from aggregate shocks shared by all well users. Distinct from the estimating equations (1) and (2), δ_t now includes both month and year fixed effects. The inclusion of these time fixed effects provides an opportunity to test if our estimates of the price elasticity of demand for agricultural water are robust to their inclusion.

The parameter of interest, β, captures the level effect of the introduction of volumetric pricing on groundwater extraction. Identification of the treatment effect hinges on the assumption that in the absence of volumetric pricing, extraction trends in the East and West would be the same. To test the parallel trends assumption we return to Figure 5 in which we condition on volumetric prices and plot out the difference in mean monthly residual water use across the two regions in the "pre-treatment" period. This figure highlights that for most months, conditional water use is balanced across the two regions and provides evidence to support the assumption that in the absence of prices, water use across the two regions would exhibit parallel trends.

5 Results

Results from the estimation of equations (1) and (2) are reported in Table 2. Column (1) reports results from an OLS regression of the log of groundwater extraction on the log of prices conditional on well fixed effects; column (2) further controls for month fixed effects; and column (3) adds controls for aggregate shocks including the log of monthly surface water use, a drought index, precipitation, growing and harmful degree days, and annual water deliveries from the State Water Project. Column (4), our preferred specification, further conditions on the annual groundwater recharge quantities in each region.

Table 2: Price Elasticity of Demand for Agricultural Groundwater

					East Only
	(1)	(2)	(3)	(4)	(5)
	$ln(Pump)$	$ln(Pump)$	$ln(Pump)$	$ln(Pump)$	$ln(Pump)$
$ln(RAC)$	-0.166***	-0.200***	-0.186***	-0.169***	-0.218***
	(0.047)	(0.049)	(0.055)	(0.057)	(0.058)
$ln(Recharge)$				-0.008	0.077
				(0.012)	(0.062)
N	55,171	55,171	55,171	55,171	22,999
R^2	0.664	0.694	0.696	0.696	0.694
Well FE	Yes	Yes	Yes	Yes	Yes
Month-of-year FE	No	Yes	Yes	Yes	Yes
Aggregate Shocks	No	No	Yes	Yes	Yes

Notes: Results are reported from an OLS regression with fixed effects. The dependent variable is the natural log of groundwater extraction for well i in month t. Standard errors clustered at the well and region-year are in parentheses. *, **, *** denote significance at the 10%, 5%, and 1% level. Aggregate shocks include the log of monthly district-level surface water use, monthly weather controls, and annual SWP deliveries. Column (5) limits the sample to wells in East Whitewater only, the region that is dominated by agricultural wells.

Our results demonstrate that volumetric groundwater prices impact groundwater use in an economically modest way, with short-run price elasticity estimates ranging from -0.16 to -0.20 across alternative specifications.[14] In our preferred specification, we find that a 1% price increase would induce a 0.17% decrease in extraction. Our estimates of the price elasticity of demand for groundwater hinge on the assumption that aggregate and regional annual shocks and intra-annual regional unobservables are not systematically correlated with prices and groundwater use. Columns (3) and (4) highlight that the price elasticity estimate is insensitive to the inclusion of a number of potential confounding observables, including monthly surface water use and weather, annual State Water Project deliveries, and the region-year recharge quantities.

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

[14]We interpret this estimate as a gross short-run elasticity because our empirical strategy identifies an effect using month-to-month variation in prices and does not attempt to unpack how the adjustment in groundwater use is achieved. However, if we assume that farmers cannot adjust land use or technology in response to these short-run price shocks, then we could interpret this estimate as an intensive margin effect. The insensitivity of the estimate to the inclusion of land use covariates in Table 3 gives credence to this interpretation.

the extent to which this estimate reflects the price elasticity of demand for agricultural groundwater, we estimate equation (2) on wells exclusively in the East Whitewater region, since pumping in this area is almost exclusively agricultural. As shown in column (6), we find that demand is slightly more responsive to price changes, with a demand elasticity of -0.22. This result lends confidence to the interpretation of the results reported in columns (1)-(4) as the short-run price elasticity for agricultural groundwater.

Table 3 further examines the sensitivity of our results to an array of additional time-varying observables that may bias our coefficient estimates. Controls for annual total acreage in agriculture (col. 1), annual crop composition (col. 2), month-by-region recycled water deliveries (col. 3), lagged groundwater prices (col. 4), a cubic regional time trend (col. 7), and quadratic regional time trend (not shown) do not alter our primary qualitative finding.[15] In theory, changes in energy prices may confound our estimation of the price elasticity 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 strong evidence in support of our main identifying assumption that time-varying unobservables are not systematically correlated with both prices and groundwater use.

To account for the impact of surface water, a substitute for groundwater, we construct an aggregate measure of monthly surface water use that we include in our preferred specification, and then examine the sensitivity of our results to the inclusion of surface water prices. Controlling for surface water use allows us to directly account for substitute goods. Deploying a basin-wide measure of this variable circumvents the empirical concern that surface water use is a choice variable influenced by many of the same factors determining well-level groundwater use. A comparison of columns (2) and (3) of Table 2, which are exclusive and inclusive of aggregate surface water consumption respectively, highlights that our elasticity estimates are stable to the inclusion of aggregate surface water use.

[15] We do find that the inclusion of more flexible regional time trends attenuates the magnitude and reduces the precision of the elasticity estimate. This occurs because much of the price variation is year-to-year, and increasing over time. This finding serves as the motivation for our difference-in-differences framework.

Table 3: Robustness of Price Elasticity of Agricultural Groundwater

	Additional Controls for							
	(1) Total Acreage	(2) Crop Composition	(3) Recycled Water	(4) Lagged Prices	(5) Canal Rates	(6) Lagged SW	(7) Cubic Trend	(8) Year FE
$ln(RAC)$	-0.143**	-0.132**	-0.160**	-0.167**	-0.155***	-0.169***	-0.128	-0.073
	(0.059)	(0.065)	(0.067)	(0.066)	(0.055)	(0.057)	(0.119)	(0.075)
$ln(RAC_{lag})$				-0.001				
				(0.032)				
N	51,185	51,185	42,425	54,601	55,171	55,171	55,171	55,171
R^2	0.697	0.697	0.703	0.696	0.697	0.696	0.697	0.697
Well FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Month-of-year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Aggregate Shocks	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Results are reported from an OLS regression with fixed effects. The dependent variable is the natural log of groundwater extraction for well i in month t. Standard errors clustered at the well and region-year are in parentheses. *, **, *** denote significance at the 10%, 5%, and 1% level. Aggregate shocks include the log of monthly district-level surface water use and monthly weather controls in all specifications, and annual SWP deliveries in columns (1)-(7). Columns (1)-(8) control one at a time for total irrigated acreage, crop composition, recycled water use, lagged prices (RAC), canal rates, lagged district-level surface water use, annual cubic regional trends, and year fixed effects.

Our elasticity estimate is also robust to the inclusion of surface water prices and lagged district-level surface water use, as reported in columns (5) and (6) of Table 3, respectively. A detailed discussion on the role of surface water deliveries and canal rates can be found in Appendix A.

5.1 Difference-in-Differences Results

Table 4 reports results from the estimation of equation (3), a difference-in-differences model that conditions on well, month and year fixed effects, and indirectly tests if underlying aggregate shocks drive our estimated price elasticities. Results indicate that the introduction of volumetric groundwater pricing led to a large reduction in monthly groundwater use of 13.7 to 15 AF. Framed differently, a jump in volumetric prices from 0 to \$36.50 per AF induced a 24% to 26% reduction in groundwater use. To compare the elasticity estimates reported in Table 2 to our difference-in-difference estimates, we estimate a semi-price elasticity of demand and compute the price elasticity under a price change of approximately 200%. In column (5) of Table 4, we estimate the same specification as column (4), except the dependent variable is measured as the natural log of groundwater extraction. We report a price elasticity of -0.15, which is is similar to those reported in the fixed effects models, albeit highly sensitive to the choice of baseline price.

These results allay lingering empirical concerns that our price elasticity estimates are driven by unobservable aggregate shocks. As shown in Figure 3, an empirical challenge in our estimation of the price elasticity of demand for groundwater is that aside from the introduction of volumetric prices in the East (Mission) in 2004 (2003), almost all the price changes experienced in the three regions occur at the same time and trend in the same direction. Columns (7-8) of Table 3 which report results from the estimation of equation (2) with a region-specific cubic time trend and year fixed effects, respectively, highlight this concern. Since year-to-year aggregate shocks explain most of the identifying variation in prices, it is difficult to separately identify the impact of price changes from the effect of yearly aggregate unobservables on groundwater use. By exploiting different price variation in our difference-in-differences framework, we can condition on year fixed effects and eliminate concerns that aggregate shocks are correlated with groundwater pumping

Table 4: Effect of Introduction of Volumetric Water Pricing on Groundwater Extraction

	(1)	(2)	(3)	(4)	(5)
	Pump	*Pump*	*Pump*	*Pump*	*ln(Pump)*
Treatment	-13.74	-14.37*	-14.33*	-14.99*	-0.30*
	(9.14)	(8.33)	(8.32)	(8.39)	(0.17)
Post	-10.42***				
	(2.50)				
Recharge				-1.06	-0.03**
				(1.16)	(0.02)
Constant	72.78***	56.53***	28.90***	29.49***	2.60***
	(3.68)	(4.24)	(9.20)	(9.26)	(0.16)
Elasticity					-0.15
N	59,830	59,830	59,830	59,830	55,868
R^2	0.585	0.635	0.638	0.638	0.697
Well FE	Yes	Yes	Yes	Yes	Yes
Month-of-year FE	No	Yes	Yes	Yes	Yes
Year FE	No	Yes	Yes	Yes	Yes
Aggregate Shocks	No	No	Yes	Yes	Yes

Notes: The table presents results from a difference-in-differences model of monthly groundwater extraction on treatment, defined as the interaction of East and the post-2004 indicator variables. Standard errors clustered at the well and region-year are in parentheses. *, **, *** denote significance at the 10%, 5%, and 1% level. Aggregate shocks include the log of monthly district-level surface water use and monthly weather controls. Column (5) transforms the dependent variable by taking the natural log to express the treatment effect as a percentage change. Elasticity is estimated with the midpoint of price.

and price changes.

5.2 Interpretation

To interpret our results and speak to their generalizability beyond our setting, we estimate heterogeneous treatment effects and place our estimate within the existing literature. First, we evaluate how the price elasticity varies depending on growing conditions, drought indices, and the time dimension of the elasticity estimate. Second, we compare our results to previous work on the price elasticity of demand for agricultural groundwater, and highlight differences across the settings and the empirical approaches.

We find that the price elasticity of demand for agricultural water differs somewhat across growing conditions, seasons, and aggregate crop composition. To evaluate heterogeneity in the price elasticity, we estimate equation (2) except we now interact the volumetric charge for groundwater with aggregate time-varying observables. Table 5 reports results; prices are interacted with the ratio of annual to perennial crops in column (1), seasonal indicator variables in column (2), precipitation and degree days in column (3), and a binary variable indicating if the CVWD was experiencing drought in column (4). As shown in column (1), our results highlight the intuitive result that when a greater portion of irrigated land is planted in annual crops as opposed to permanent crops, demand is more elastic to changes in price. Column (2) reveals that the price elasticity of demand varies across seasons, and aligns with growing conditions in California. During the summer months which coincide with the peak of the growing season, demand is insensitive to price, and during the relatively wet and dormant winter season demand is most elastic, with an estimated elasticity of -0.25. Column (3), which provides a different snapshot of the results presented in column (2), highlights that in relatively cold temperatures demand is most elastic, and becomes less sensitive to prices as growing degree days increase and growing conditions become more favorable. In column (4) we find that the demand becomes slightly more inelastic in the presence of a coarse proxy for drought. This implies that during periods of abnormal dryness, demand for groundwater may be less sensitive to changes in prices.

Table 5: Heterogeneity of the Price Elasticity of Demand for Agricultural Groundwater

	(1) Crop Composition	(2) Seasons	(3) Precip/Temp	(4) Drought	(5) Annual Elasticity	(6) Full Cost Elasticity
lnRAC	-0.020	-0.109*	-0.408***	-0.166***	-0.202***	-0.371***
	(0.099)	(0.058)	(0.125)	(0.057)	(0.068)	(0.098)
lnRAC × AnnualCrop	-0.246*					
	(0.129)					
lnRAC × Winter		-0.137**				
		(0.051)				
lnRAC × Spring		-0.041				
		(0.031)				
lnRAC × Fall		-0.027				
		(0.023)				
lnRAC × Precip			-0.108			
			(0.095)			
lnRAC × Precip^2			0.083			
			(0.066)			
lnRAC × GrowDD			0.042***			
			(0.015)			
lnRAC × HarmDD			-0.002			
			(0.003)			
lnRAC × Drought				0.010*		
				(0.005)		
N	51,185	55,171	55,171	55,171	5,559	56,871
R^2	0.697	0.697	0.697	0.696	0.887	0.696
Well FE	Yes	Yes	Yes	Yes	Yes	Yes
Month-of-year FE	Yes	Yes	Yes	Yes	Yes	Yes
Aggregate Shocks	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Results are reported from an OLS regression with fixed effects. The dependent variable is the natural log of groundwater extraction for well i in month t. Standard errors clustered at the well and region-year are in parentheses. *, **, *** denote significance at the 10%, 5%, and 1% level. Aggregate shocks include the log of monthly district-level surface water use, monthly weather controls, and annual SWP deliveries. Drought is a dummy variable equal to 1 if any area in Riverside county is in drought. Annual Crop is the fraction of agricultural land in Coachella Valley planted in annual crops. Full cost elasticity adds \$16/AF in all regions as a proxy for energy costs.

A difference between our price elasticity estimate and that typically found in the literature is that the agency-imposed pumping fee we evaluate does not equal the full per-unit cost of groundwater extraction (Hendricks and Peterson 2012; Smith et al. 2017). The full price per acre-foot of groundwater extraction comprises the RAC and the energy costs to pump a unit of groundwater to the surface. Energy extraction costs depend primarily on the depth to the water table and energy prices. Using data and calculations explained in Appendix C, we estimate that the marginal energy extraction cost for pumping is \$16/AF on average in our setting or around 16% of the total cost. While we lack sufficient groundwater depth data to estimate this cost at a more disaggregated level, for completeness we estimate the price elasticity of demand after simply adding \$16/AF to the RAC. As shown in column (6) of Table 5, the inclusion of energy extraction cost makes demand more elastic, with a reported elasticity of -0.37.

Beyond pumping costs, our empirical setting and research design differ from existing price elasticity estimates along a number of relevant dimensions. Table 9 in Appendix B summarizes price elasticity papers published since the Scheierling et al. (2006) review, and makes explicit the empirical strategy, price variation, and empirical setting that is the focus of each paper. A key distinction among studies is the role of surface water supplies. One strand of work focuses on surface water demand, and uses market transaction data or surface water prices and an instrumental variables approach (Schoengold et al. 2006; Wheeler et al. 2008; Hagerty 2019). Most of the recent work on groundwater demand investigates this question in locations where surface water supplies are unavailable (Gonzalez-Alvarez et al. 2006; Hendricks and Peterson 2012). While our empirical setting is one where farmers trade off between surface and groundwater supplies, data on surface water supplies are only available at an aggregate scale. This aggregate measure allows us to control for the possibility that surface water supplies may confound estimation of the price elasticity, but precludes us from empirically disentangling how farmers substitute across these sources.

When compared to previous annual surface and groundwater elasticity estimates, we find demand for agricultural groundwater in the Coachella Valley to be relatively inelastic. Some of these differences are driven by measurement choices, specifically our decisions to exclude pumping costs and focus on a monthly as opposed to an annual estimate. We use Smith et al. (2017), a study that uses volumetric pricing and panel data to estimate an annual gross price elasticity for groundwater of -0.77, to illustrate this point. While institutional and empirical differences make a strict comparison difficult, measurement choices explain some of the divergence in elasticity estimates.[16] When we estimate an annual elasticity gross pumping costs, we report an estimated elasticity of -0.46. We choose to focus on a monthly price elasticity estimate net of energy costs because (1) monthly measures of groundwater extraction more accurately reflect the decision-making process and (2) the exclusion of energy pumping costs eliminates amplification and attenuation bias due to systematic measurement error (Mieno and Brozoviĉ 2017).

6 Measuring the Gains from Trade

Water markets that allow for trading between agricultural and urban users poses an oft-discussed strategy to more efficiently manage scarce water resources.[17] However, quantifying the efficiency gains from water trading is challenging. First, substantial administrative, transport, and legal costs are involved with water transactions across different political and physically distant jurisdictions, and it is empirically challenging to account for these transaction costs in water trades (Regnacq et al. 2016; Ayres et al. 2018; Hagerty 2019). Second, it has been difficult to obtain micro-level evidence on the price elasticity of demand for agricultural water, and even more so in an area where estimates of the urban price elasticity of demand also exist.

Our research setting allows us to overcome some of these obstacles. We focus on the gains from trade between cities and farmers served by the CVWD. These entities are located in a single geographic and political jurisdiction, 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

[16] Smith et al. (2017) evaluate the effect of an increase in a self-imposed volumetric fee, relative to users without volumetric pricing.

[17] California has some experience with water transfers both within and across water districts. However, water trading in the state is subject to heavy regulatory oversight, features lengthy approval processes, and often local restrictions. These factors deter or prohibit many otherwise beneficial trades.

with transporting water are minimal. Low transaction costs are likely to characterize much of the groundwater trading that could occur under SGMA.[18] Another distinguishing feature of our setting is that we are able to construct parameters using observational data on prices and consumption, and directly estimate the price elasticity for agricultural water. Despite these features, we still rely on a number of important assumptions. First, we impose functional forms on demand for agricultural and urban groundwater. Second, we assume the existence of well-defined and enforceable property rights for groundwater and the absence of environmental externalities arising from trade.

6.1 Theoretical Framework for Water Trading

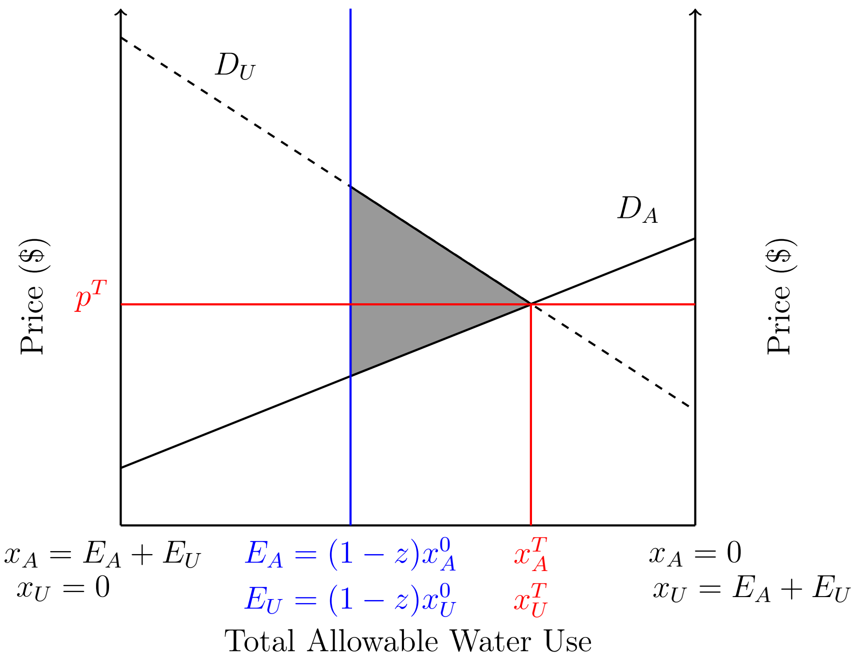
In this section, we introduce a simple theoretical framework to evaluate the efficiency gains from the establishment of water trading among urban cities and agricultural users served by a single water district. We conceptualize the gains from trade under a scenario in which the regulator restricts aggregate baseline water use, and frictionless trading occurs between urban and agricultural users. The model formalizes the relationships between demand for agricultural and urban water, initial water allocations, and the gains from trade. This allows us to quantify the benefits from trade as a function of estimated demand parameters and observables, and examine the relative importance of each parameter in determining the magnitude of the gains from trade.

Consider a market comprised of two types of users - an agricultural water user (type A) and an urban water user (type U) - that consume water from a single source. Assume that users are homogeneous within their type. Let $P = D_U(x)$ and $P = D_A(x)$ denote the inverse aggregate demand curves for urban and agricultural water, respectively, where x represents the quantity of water demanded. The baseline quantity demanded at some fixed marginal cost of consumption is denoted x_i^0 for $i \in (A, U)$.

Suppose that drought imposes a shock to the water supply; a regulator responds by imposing a mandatory reduction in aggregate water use for all users represented by $z \in [0, 1]$; and trading can occur. This mandatory reduction results in an initial allocation

[18]Two costs that remain in our setting and more generally for the deployment of SGMA are the assignment of property rights for groundwater and the establishment of a cap on groundwater pumping.

Figure 6: Gains from Ag-Urban Trade (Uniform Standard)



Notes: D_U and D_A denote inverse aggregate demand curves for urban and agricultural water, respectively. D_U is plotted on the left vertical axis and D_A is plotted on the right vertical axis. The width of the x-axis, given by $E_A + E_U$, measures the total quantity of water available for agricultural and urban users. Total available water is fixed on the x-axis such that any point along it represents a different combination of water use across sectors. Moving left-to-right along the x-axis, the quantity of urban consumption increases, and moving right-to-left the quantity of agricultural consumption increases. The z uniform conservation mandate results in consumption quantities denoted by $E_A = (1-z)x_A^0$ and $E_U = (1-z)x_U^0$ for agriculture and urban use, respectively, the quantities consumed by each sector under a uniform standard. The quantity of water consumed by agricultural and urban types after trade is given by x_A^T and x_U^T, and occurs where the marginal net benefits are equal across user types. The shaded area represents the gains from trade relative to the uniform standard.

of water use, denoted by $E_i = (1-z)x_i^0$ for $i \in (A, U)$. If the marginal value product for urban consumption evaluated at the constraint (E_U) is different than the marginal value product for agriculture at the agricultural constraint (E_A), then there exists some set of prices where trading will take place. 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 quantities describe the quantity consumed by each type after trade. The difference between E_i and x_i^T determines the quantity of water traded.

Figure 6 expresses this trading scenario with linear demands. Urban water demand D_U is depicted on the left vertical axis and agricultural water demand D_A is depicted on the right vertical axis. The width of the horizontal axis measures the total quantity of water available: $E_A + E_U = (1-z)x_A^0 + (1-z)x_U^0$. Any point along the horizontal axis represents a different combination of water use in each of the two sectors, holding constant the total water endowment. Moving left-to-right, urban water use increases, agricultural water use decreases, and their combined consumption remains constant. Moving right-to-left, the reverse holds. This orientation allows us to visualize the optimal allocation and associated surplus relative to alternative initial allocations, holding the total amount of available water constant. The initial allocation considered in Figure 6 is a z uniform standard that results in consumption quantities denoted by $E_A = (1-z)x_A^0$ and $E_U = (1-z)x_U^0$ for agricultural and urban use, respectively. If trade is allowed, it will occur until the marginal net benefits are equal across the two sectors, and corresponds to consumption quantities, x_A^T and x_U^T. The shaded triangle illustrates the gains from trade relative to a uniform standard.

Mathematically, the gains from trade, denoted by G, can be expressed as the area,

$$G = \int_{E_U=(1-z)x_U^0}^{x_U^T} D_U(\tau)d\tau - \int_{x_A^T}^{E_A=(1-z)x_A^0} D_A(\tau)d\tau, \qquad (4)$$

and depend on the shape of the demand curves, the initial allocation of water between types, and the aggregate quantity of required water abatement.

6.2 Analytical Framework and Parameters

Our simulation focuses on quantifying surplus changes from four policy counterfactual scenarios. Our first scenario measures the change in surplus from the introduction of volumetric pricing for agricultural groundwater in the CVWD. It imposes no change in the quantity of water available, and does not consider the gains from trade. In a second scenario, we take CVWD agricultural water pricing as given, and assess the magnitude of remaining pricing distortions across urban and agricultural users. This scenario allows for existing water supplies to be reallocated across agricultural and urban water users. A third scenario begins by imposing a 25% mandatory reduction in urban water use, and is intended to mirror the 2015 California conservation mandate that (in aggregate) required urban water users to reduce water use by 25% relative to 2015 quantities. It then simulates market behavior and the gains from trade if urban users could comply with this restriction through trade with agricultural users. In a final scenario, we impose a uniform standard that mandates urban and agricultural water use to decrease by a percentage of baseline water use. We then consider behavior if a uniform standard were replaced by cap and trade, thereby allowing for a cost-effective reallocation of water across urban and agricultural users. This scenario allows us to weigh in on the potential gains from trade under a range of uniform water supply reductions.

We impose some simple structure on our theoretical framework to derive analytical solutions. We assume the demand curves exhibit constant elasticities: $x_U(P) = \gamma_U P^{-\eta_U}$ for urban water and $x_A(P) = \gamma_A P^{-\eta_A}$ for agricultural water. The price elasticity of demand is denoted by η_i for i $\in (U, A)$. Introducing this simple structure allows us to solve for the gains from trade as a function of demand parameters, the initial endowments of water, E_U and E_A, and the optimal quantity of water consumed by agricultural and urban types after trade, x_A^T and x_U^T:[19]

$$G = \int_{E_U}^{x_U^T} (\frac{\tau}{\gamma_U})^{-\frac{1}{\eta_U}} d\tau - \int_{x_A^T}^{E_A} (\frac{\tau}{\gamma_A})^{-\frac{1}{\eta_A}} d\tau$$

$$= \frac{\gamma_U}{1-\frac{1}{\eta_U}} \left[(\frac{x_U^T}{\gamma_U})^{(1-\frac{1}{\eta_U})} - (\frac{E_U}{\gamma_U})^{(1-\frac{1}{\eta_U})} \right] - \frac{\gamma_A}{1-\frac{1}{\eta_A}} \left[(\frac{E_A}{\gamma_A})^{(1-\frac{1}{\eta_A})} - (\frac{x_A^T}{\gamma_A})^{(1-\frac{1}{\eta_A})} \right]. \quad (5)$$

We use equation (5) to simulate how the gains from trade change with different water conservation policies and different parameter values. Table 6 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 source.

Our simulation utilizes an estimate of the price elasticity of demand for urban water, denoted η_U, from Baerenklau et al. (2014), and uses the price elasticity for agricultural water, denoted η_A, reported in column (4) of Table 2. The Baerenklau et al. (2014) elasticity parameter was estimated using a panel of household-level water billing data

[19] To solve for these latter quantities, we make use of the relationship between the water allocated and consumed in these sectors: $x_A^T + x_U^T = E_U + E_A$. We then equate demands and solve the system of two equations in two unknowns.

Table 6: Parameter Estimates

Parameter	**Symbol**	**Estimate**	**Source**
Urban Elasticity	η_U	-.76	Baerenklau, Schwabe, and Dinar (2014)
Agricultural Elasticity	η_A	-.17	Column (4) of Table 2
Baseline Urban Water Use	x_U^0	62,151 AF	2015 aggregate use; UWMP
Baseline Agricultural Water Use	x_A^0	233,219 AF	2015 aggregate use; well data
Baseline Urban Water Price	c_U	\$233.70/AF	CVWD variable production cost
Baseline Agricultural Water Price	c_A	\$100.50/AF	CVWD agricultural price data
Urban Coefficient	γ_U	\$3,923,094	Calculated with c_U, x_U^0
Agriculture Coefficient	γ_A	\$510,660	Calculated with c_A, x_A^0

Notes: This table lists the relevant simulation parameters, parameter values, and data source. The symbols map directly to the analytical framework. Data on urban water use come from the urban water management plan published by the CVWD, and data on agricultural water use come from well-level data provided by the CVWD.

from a nearby urban water utility in Riverside County that also uses a budget-based tiered pricing structure.[20] To reflect the range of existing urban price elasticity estimates and differences in agricultural price elasticity estimates inclusive and exclusive of energy extraction costs, we model the sensitivity of our results to a range of parameter values in Figure 7.

Baseline agricultural water use and baseline urban water use, denoted as x_A^0 and x_U^0, are necessary inputs in the calculation of the water conservation target and the determination of the isoelastic urban and agricultural water demand functions. Our measure of baseline agricultural water use is equal to the sum of groundwater extraction across all farms in the CVWD in all months of 2015, and amounts to 233,219 AF. Aggregate residential water use from all households in CVWD in 2015 totals 62,151 AF or roughly 1/4 of annual agricultural water use. The baseline agricultural water price, c_A, is measured as the sum of the RAC and the energy extraction cost. We measure baseline urban water prices, c_U,

[20]This estimate is relatively more elastic than other recent estimates of residential water demand: -.12 in Santa Cruz, California (Nataraj and Hanemann 2011); -.43 to -1.14 depending on the level of consumption in Chapel Hill, North Carolina (Wichman 2014); and -.13 in Melbourne, Australia (Brent and Ward 2019). More details can be found in Appendix B.

as the average variable production cost or the cost incurred by a utility to produce and supply the next unit of water.[21] Details on the construction of the baseline prices are provided in Appendix C. The parameters labeled γ_i for $i \in (U, A)$ are calculated using an observed point on the demand curve, the price elasticity of demand, and our isoelastic functional form assumption.[22] We use the point on the agricultural and urban demand curves given by (x_A^0, c_A) and (x_U^0, c_U), respectively.

6.3 Change in Surplus from Water Pricing

We begin by quantifying the change in surplus from the introduction of volumetric pricing for agricultural groundwater in some regions of the CVWD. This policy change in the East Whitewater and Mission Creek regions increased the cost to pump groundwater from \$16/AF to \$54/AF on average, taking energy extraction costs into account. We measure the change in surplus as the integral under the aggregate demand curve for agricultural water in the CVWD over the range of the observed price change:

$$\triangle CS = \int_{\$16}^{\$54} \gamma_A \tau^{-\eta_A} d\tau = \$10,718,909. \tag{6}$$

This price increase led to a \$10.7 million change in surplus. This constitutes roughly 45% of the market size for agricultural water in 2015, where the large impact is reflective of the magnitude of the price change. When evaluated at the bounds of $\hat{\eta}_A$ defined by its 95% confidence interval, this estimate ranges from \$9.4 to \$12.15 million.

Despite the large increase in agricultural prices experienced in the region, distortions in water pricing between the agricultural and urban sectors still persist, sustaining inefficiencies in the allocation of water across sectors. The CVWD reported a variable production cost of \$233.70/AF for residential water which is roughly double the price per AF that

[21] In our setting, residential users the cities served by CVWD pay an average retail price of \$721.13 per AF, over 7 times the \$100.50 per AF that agricultural users pay. However, in the residential water setting, fixed costs are often bundled into volumetric prices, so price differences across residential and agricultural users may actually reflect differences in the cost to treat and distribute water to urban users.

[22] Our isoelastic functional form assumption is motivated by the existing empirical literature on the price elasticity of demand for urban and agricultural water use, and reflects the status quo of a constant elasticity of demand functional form (Nataraj and Hanemnn 2011; Hendricks and Peterson 2012; Baerenklau et al. 2014; Pfeiffer and Lin 2014; Wichman et al. 2016; Edwards et al. 2018; Hagerty 2019). One caveat in the interpretation of these parameters is that our calculation leans on out-of-sample predictions.

Table 7: Changes in Welfare (in millions)

Initial Allocation	No Cutback	25% Urban Cutback	
		No Trade	With Trade
Observed	-$1.25 [-.623, -1.57]		
Efficient	0	-$0.683 [-0.668, -0.713]	-$0.386 [-0.313 , -0.541]

Notes: The table measures the change in welfare under various policy scenarios. All values are expressed relative to the optimal allocation, which is defined as the point where marginal net benefits are equal across sectors and labeled "Efficient, No Cutback." In the cell labeled "Observed, No Cutback" we measure the costs from the observed allocation in water that arises from differences in prices across agricultural and urban users. The columns labeled "25% Urban Cutback" measure the welfare lost under an urban mandate in the presence and absence of trade. The 95% confidence intervals reported in brackets are based on uncertainty in the estimation of the price elasticity of agricultural water demand and were derived by calculating welfare changes at the bounds of the 95% confidence interval for $\hat{\eta}_A$.

agricultural users pay. Trading may serve as a mechanism to correct these outstanding allocative inefficiencies. Table 7 reports the change in welfare that could accrue under frictionless trading, using parameter estimates from Table 6. The cell labeled "Observed, No Cutback" highlights that the costs from price differences total $1.25 million per year and that, despite the large agricultural price increases experienced prior to 2015, inefficiencies remain. If trading operated as the mechanism to mitigate these inefficiencies, a meaningful amount of trade would occur, with urban users purchasing (agricultural users selling) 18,840 AF of water. The equilibrium market price for water would amount to $165 per AF, a price that is 70% higher than the current price for agricultural water. The magnitude of these prospective gains from trade can be described as roughly 3.3% of the district's $37.96 million annual variable groundwater expenditures. In other regions of California where groundwater remains unpriced, the potential gains from trade are likely to be larger.

6.4 Sensitivity Analysis

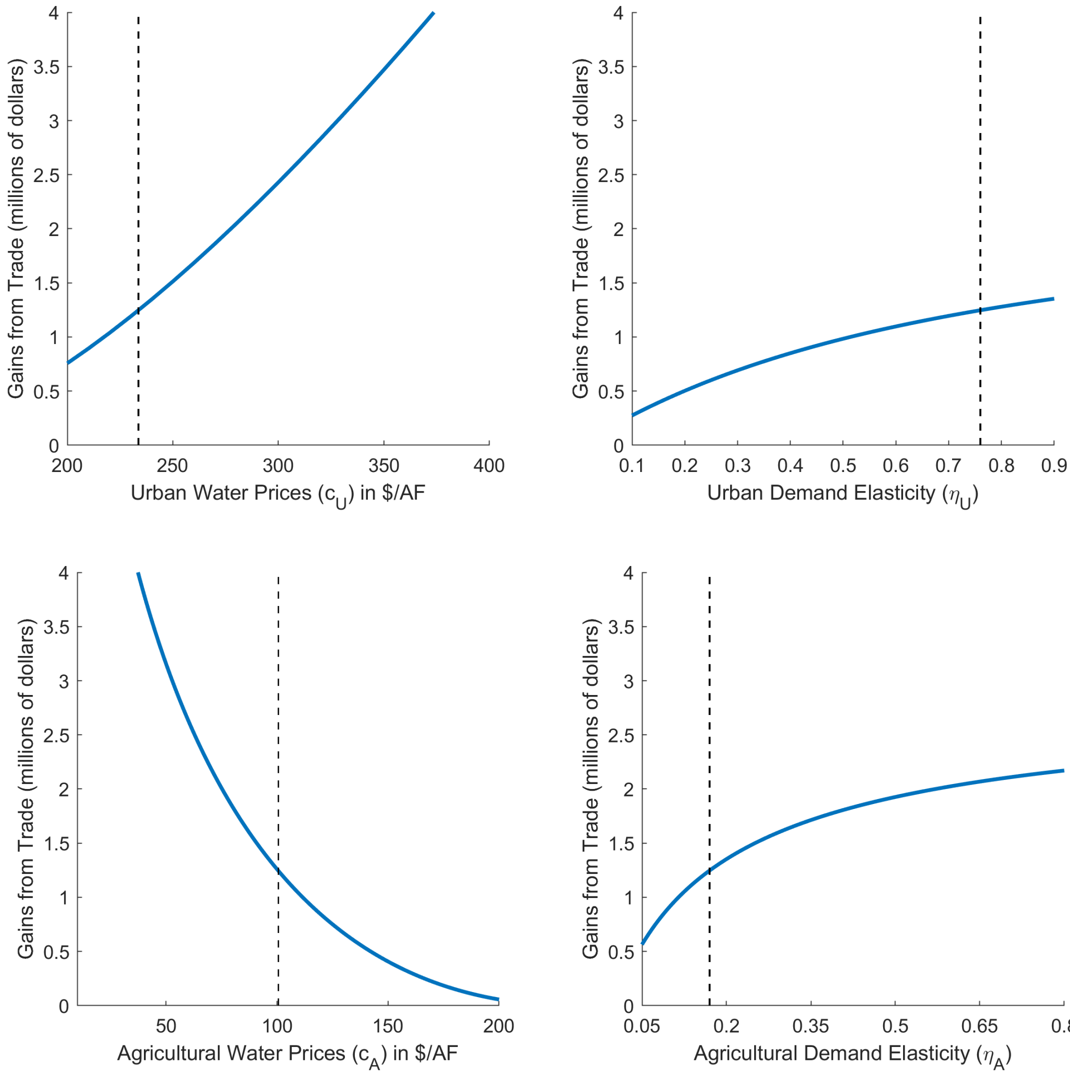
Before simulating market outcomes under curtailment scenarios, we conduct a sensitivity analysis to evaluate how the simulated gains from trade vary under a range of possible parameter values. This analysis helps us understand the generalizability of our simulated outcomes to settings that feature different demand elasticities and baseline water rates. It also showcases the relative importance of each parameter in influencing the magnitude of the gains from trade. Figure 7 illustrates how the gains from trade change as we vary the agricultural price elasticity, η_A, the urban price elasticity, η_U, the urban price, c_U, and the agricultural price, c_A, holding all else constant. The parameter values for CVWD are displayed with a vertical line in each panel of Figure 7. At the vertical line, the gains from trade are equivalent in each panel by construction.

As shown in the right-hand side panels of Figure 7, the gains from trade grow as either agricultural or urban demand become more elastic, and are relatively more sensitive to the agricultural price elasticity of demand. Our first take-away from the agricultural elasticity sensitivity figure is that our -0.17 elasticity estimate provides a conservative measure of the potential gains from trade. If we measured the price elasticity inclusive of pumping costs or with an annual as opposed to monthly time step, the gains would be larger. This is because, given the other parameter values, as demand becomes more elastic, the quantities traded are more responsive to price changes, so more trading occurs. A second visual result suggests that the gain from trade appear to be more sensitive to the agricultural elasticity. This emerges from a comparison between the urban and agricultural price elasticities in determining the gains from trade. If the agricultural parameter value experiences a small perturbation, the change in the gains from trade is larger than if that same perturbation occurred for the urban elasticity value.[23] This underscores the importance of obtaining credible estimates of agricultural price elasticities. We see that under an array of residential price elasticity estimates, which encompass other existing estimates in the literature, the gains from trade remain in the $1-1.5 million range.

The left-hand side panels of Figure 7 illustrate the sensitivity of the gains from trade to the baseline urban and agricultural water price, respectively. The upper panel demonstrates that as the water price for urban users declines, and agricultural and urban prices converge, the gains from trade decrease. As shown in the bottom panel, as agricultural water rates increase, the distortion between agricultural and urban water prices shrinks,

[23]This occurs in part because in our setting agricultural water demand is much more inelastic than urban water demand, implying that small changes in the elasticity will lead to larger changes in the gains from trade. It also is a reflection of differences in prices and water allocations, factors held constant in the sensitivity analysis.

Figure 7: Sensitivity of the Gains to Demand Parameters



Note: This figure showcases the sensitivity of the gains from trade estimate to changes in four parameters, respectively: the baseline urban water price, urban demand elasticity, baseline agricultural water price, agricultural demand elasticity. The vertical lines mark parameter values from Table 6. For this simulation, the conservation policy is held constant at 0% (no supply shock).

and the gains from trade decrease. Across California, we expect agricultural water prices to exhibit substantial geographic variation due to differences in well depths and energy rates. Our rate likely provides an upper bound of agricultural water prices, and thus a lower bound on the gains from trade. This is because it includes pumping costs and the RAC, whereas most water districts lack an agency-imposed agricultural pumping fee.

6.5 Drought Mandate and Gains from Trade

We now evaluate the change in surplus if cities in the CVWD could have complied with the statewide 25% urban conservation mandate through trade with agricultural users. To isolate the increase in surplus attributable to policy instrument choice, this scenario assumes that in the absence of regulation the allocation of water across user groups is efficient: ($x^*_A = 214,379; x^*_U = 80,991$). A 25% reduction in baseline urban water use translates to an urban water supply reduction of 20,248 AF.

Table 7 measures the change in surplus under an urban drought mandate, both with and without frictionless trade between sectors. All welfare estimates are expressed as the change relative to the efficient allocation in absence of a cutback, "Efficient, No Cutback." Simulation results indicate that in the absence of trade, a 25% urban mandate would reduce welfare by $683,000 or roughly 5% of pre-mandate urban water expenditures. A comparison of the welfare changes in the absence and presence of trade reveals that trading could lower the welfare costs by 43%, reducing the deadweight loss to $386,000. Our simulation suggests that 7,833 AF would be sold by agricultural to urban users at a market-clearing price of $205/AF, implying that 38.6% of the required conservation would have shifted to the agricultural sector. This highlights that even in the absence of pre-existing distortions, market-based approaches can substantially reduce the costs to comply with water conservation mandates.

6.6 Supply Curtailments and Gains from Trade

As a first step towards understanding the role that water markets could play in climate change adaptation and compliance with SGMA, we simulate the gains from trade under a range of water supply curtailments experienced uniformly across sectors, ceteris paribus.

We view this exercise as a starting point for using the microeconomic framework set forth in this paper, and acknowledge that we increasingly rely on out-of-sample predictions and the structure imposed on water demands to simulate market behavior. The parameters used in this simulation are specific to the time period 2000-2016, and may change depending on future water and agricultural policies, demographic trends, or long-run changes in water allocations. For these reasons, we interpret our results as projections on the prospective gains from trade, holding all else equal.

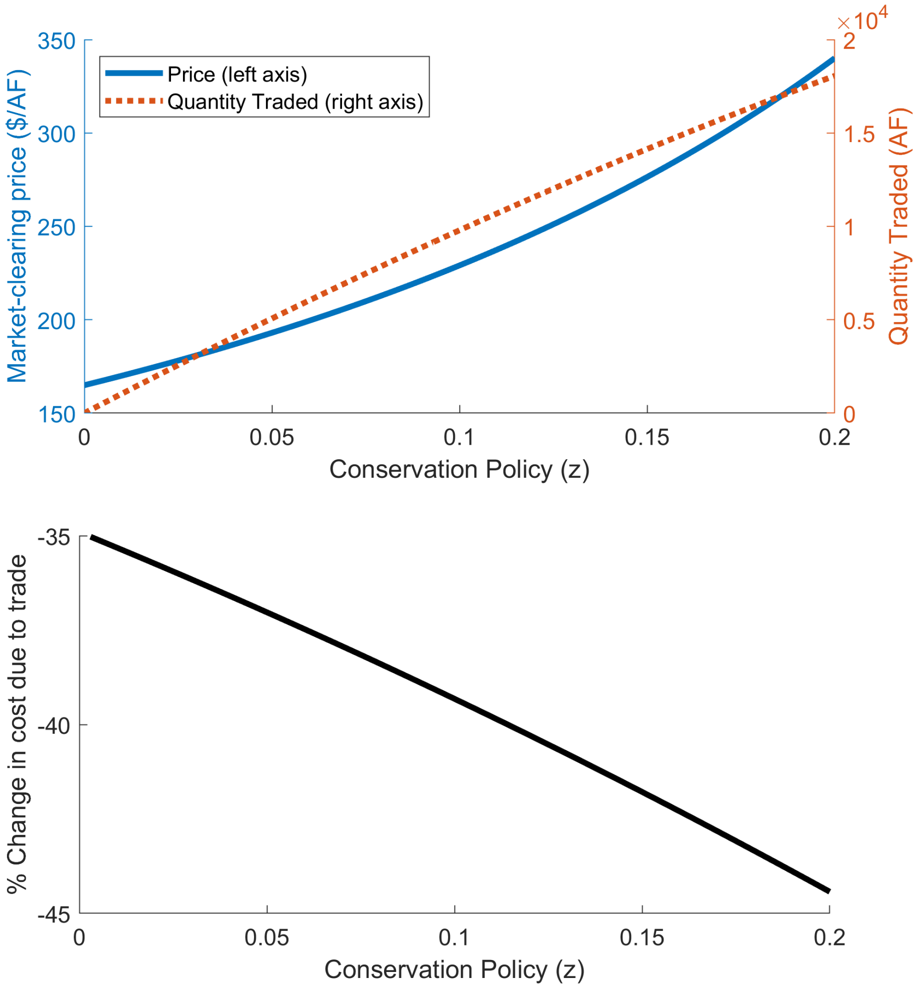
The top panel of Figure 8 plots the market-clearing price (left vertical axis) and quantity traded (right vertical axis) between agricultural users and cities under a range of water supply curtailments. Informed by climate change studies, the horizontal axis denotes the stringency of the water conservation mandate and ranges from 0 to 20% of aggregate baseline water use.[24] Importantly, we again focus on the gains associated with instrument choice by seeding an initial allocation that equates marginal net benefits across sectors. Moving from left to right, our simulation highlights that as the conservation policy increases, the market-clearing price for groundwater and the quantity of groundwater sold increases. The equilibrium price for groundwater rises from $165 in absence of a mandate to $340 per AF at a 20% conservation mandate, reflecting the increased scarcity of water. In the presence of curtailments, water is sold from urban users to agricultural users. This occurs because prior to curtailments, the marginal net benefits of consumption are equal across user types, and agricultural demand for water is relatively less elastic. As the conservation policy becomes more stringent, the quantity traded increases because the difference in the marginal willingness-to-pay across sectors becomes greater.

The bottom panel of Figure 8 provides a different snapshot of the same simulation. It shows the extent to which the welfare costs of a uniform standard could be mitigated with trade, as the conservation policy changes from 0% to 20% of aggregate baseline use. The vertical axis reflects the savings from trade relative to a uniform standard, and is expressed as a percentage.[25] The gains from trade are substantial, with the cost savings growing

[24]This range was informed by research conducted as part of California's 4th Climate Change Assessment which asserts that (1) by 2050 California agriculture could face climate-related water supply shortages of 16% under certain rainfall scenarios and (2) by 2100 water supply from snowpack is projected to decline by up to 2/3 (Huang, Hall, and Berg 2018).

[25]Explicitly, we calculate it as $\%\triangle(z) = \frac{DWL_T(z) - DWL_U(z)}{DWL_U(z)} * 100$ where $DWL_U(z)$ is the deadweight

Figure 8: Price, Quantity, and Gains as Policy Changes (Optimal Baseline)



Note: The top panel of the figure illustrates the market-clearing permit price on the left y-axis and the quantity traded in equilibrium in acre-feet (AF) on the right y-axis as the conservation policy changes, given an initial starting point that represents an optimal allocation across urban and agricultural users. Similarly, the bottom panel plots the gains from trade relative to the welfare lost from a uniform standard as the conservation policy changes from a 0% to 20% reduction in aggregate baseline water use: $\%\triangle = \frac{DWL_T(z) - DWL_U(z)}{DWL_U(z)} * 100 = \frac{Gains(z)}{DWL_U(z)} * 100$ where $DWL_U(z)$ is the deadweight loss of a z% uniform cut-back in the absence of trade and $DWL_T(z)$ is the deadweight loss of a z% uniform cut-back in the presence of trade. It shows the extent to which the welfare cost of a uniform standard could be reduced with trade.

from 35% to 45% as the uniform curtailment increases. Over the range of curtailments considered in our simulations, the cost savings increase in policy stringency because the welfare costs of a uniform standard increase, as does the difference in willingness-to-pay across user groups. Our simulation shows that the costs from water supply reductions can be substantially reduced if users can respond to curtailments through trade. Water trading presents a strategy to meaningfully reduce the costs of climate change and compliance with SGMA.

7 Conclusion

In this paper, we begin by estimating the price elasticity of demand for agricultural groundwater, providing one of the first direct estimates of this parameter. To identify this elasticity, we take advantage of monthly, well-level panel data on agricultural groundwater extraction in a water district that charges three geographically distinct volumetric prices for groundwater. We find that prices have a modest effect on agricultural groundwater extraction, with elasticity estimates ranging between -0.16 and -0.2.

While our price elasticity estimate is restricted to a single California groundwater basin, the Sustainable Groundwater Management Act will regulate groundwater at the local level, so understanding the basin-level response to prices is critical for the design of effective groundwater policies. What we are lacking are comparable estimates for other water districts throughout the state. This is driven by the general absence of both groundwater metering for agricultural water use and volumetric groundwater pricing for agriculture. As California's new groundwater law transitions from design to implementation, agricultural groundwater metering will become more common and some basins may introduce pricing to comply with the regulation. Our work informs the use of volumetric pricing as a tool for basin-level compliance with the Sustainable Groundwater Management Act.

We next apply our elasticity estimate to calculate the impact of pricing distortions on

loss of a z uniform standard and $DWL_T(z)$ is the deadweight loss of a z curtailment in the presence of trade. The numerator measures the difference in the deadweight loss between the two policy instruments, i.e., the gains from trade, and the denominator captures deadweight loss of the uniform standard. Details, including analytical expressions and a graph of this DWL area, can be found in Appendix C.

surplus. Our simulation reveals that the introduction of volumetric pricing for agricultural groundwater led to a change in surplus of \$10.7 million, equivalent to roughly 43% of agricultural expenditures on groundwater. Even with volumetric pricing for agricultural groundwater, distortions in water prices across the agricultural and urban sectors remain. In the CVWD, these distortions impose costs of \$1.25 million, roughly 3.2% of annual regional groundwater expenditures. If we extend this simulation and perform a back-of-the envelope calculation of the change in surplus from correcting pre-existing pricing distortions across California, the savings amount to \$580 million, or roughly 19% of statewide water expenditures (Hanak et al. 2014).[26] Water trading or efficient pricing within groundwater basins offer mechanisms for correcting these distortions.

Our simulation also highlights that intra-basin trading between agricultural and urban users yields large welfare gains in the presence of water conservation mandates. Markets could have substantially reduced the cost of compliance with California's 2015 urban water conservation drought mandate. Our model also projects that relative to a uniform standard, a water market could reduce the annual costs of meeting a uniform 20% water curtailment by almost 45%. This suggests that groundwater markets could be deployed as an instrument to cost-effectively comply with groundwater use restrictions under SGMA. More generally, they present an important and promising adaptation to mitigate the costs from water supply curtailments projected under climate change.

[26]According to Dieter et al. (2018), statewide water use in 2015 amounted to 21.3 million AF for irrigation and 5.7 million AF for public water supply, respectively. For this calculation, we hold the price elasticities and the baseline urban price the same, but substitute the baseline agricultural water price figure for one that only includes energy extraction costs (\$16/AF instead of \$100.50/AF).

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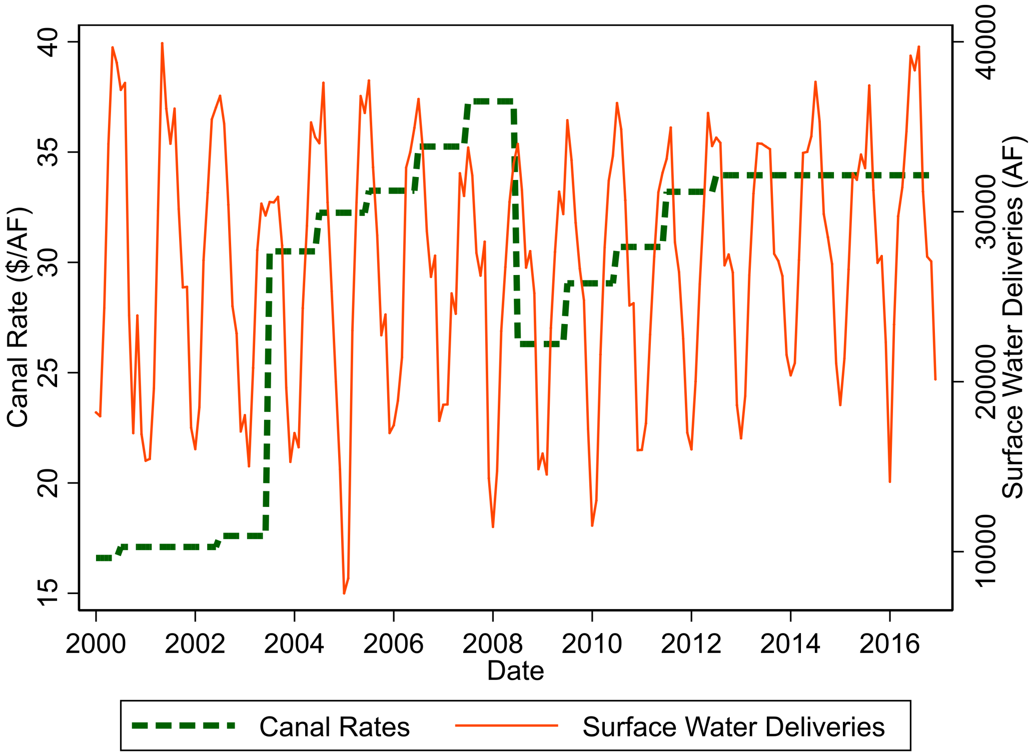
A Appendix: Surface Water Prices

CVWD's surface water is delivered via the Coachella Canal from the Colorado River. The water district has had rights to this water since the 1931 Seven Party Agreement that allocated California's apportionment of the Colorado River. The Quantification Settlement Agreement, which authorized a transfer of state water project water from Metropoliton to CVWD in 2003, supplemented the 1931 agreement and ultimately determined CVWD's base allotment of 330,000 AF per year. Due to the seniority of these water rights on the Colorado River, the aggregate deliveries do not change much from year-to-year. Monthly aggregate consumptive use as reported by the Bureau of Reclamation and displayed in Figure 9, exhibits seasonal variation that reflects the agricultural growing season.

Surface water rates consist of a per-AF use charge, a per-AF Quagga Mussel Control surcharge, and a per-day gate charge. The same canal rates apply to all agricultural users and thus do not vary regionally like the RAC. As such, canal delivery data is not collected by region. Just like with the groundwater fees, the CVWD periodically performs a "Cost of Service" report on canal operations to evaluate the need for rate increases. When needed, the reports recommend a rate increase (and sometimes a change in structure) in order to ensure the financial stability in the Canal Water Fund. Aggregate agricultural canal rates ($/AF) are shown in Figure 9. When a rate adjustment is made, it occurs at the start of the fiscal year. Costs associated with the maintenance of the Coachella Canal and delivery of surface water are independent of the costs associated with the recharge fund. Our understanding is that these are treated as separate funds and operations, rates are changed based on cost of service, and the rate changes across surface and groundwater are not directly related to each other. However, canal rates may impact groundwater fees indirectly, because surface water is used to artificially replenish the aquifer.

In the CVWD, surface water prices may affect groundwater use through two channels. First, since surface water is a substitute good for groundwater, changes in the price of surface water (all else equal) should inversely impact groundwater use. Second, surface water sources, and hence surface water prices, may influence groundwater prices indirectly. This latter relationship implies that increases in surface water prices will lead to a decrease in groundwater use, through the channel of groundwater prices. It also highlights the

Figure 9: Canal Rates and Surface Water Deliveries



Notes: The figure plots monthly surface water rates ($/AF) on the left y-axis and monthly aggregate surface water deliveries (AF) on the right y-axis.

empirical challenge posed by surface water prices. A failure to explicitly account for them may bias coefficient estimates on groundwater prices, but to the extent that surface water prices serve as a proxy for groundwater prices, conditioning on them may also introduce bias and lead to attenuated estimates of the price elasticity of demand.

To account for the importance of substitute goods, we construct an aggregate measure of monthly surface water use that we include in our preferred specification, and then examine the sensitivity of our results to the inclusion of surface water prices. Controlling for surface water use allows us to directly account for substitute goods. Constructing a basin-wide measure of this variable circumvents the empirical concern that surface water use is a choice variable influenced by many of the same factors determining well-level groundwater use. In aggregate, the surface water use of a single user should not have a meaningful impact on basin-wide water use.

Table 8: The Role of Surface Water Rates

					East Only
	(1)	(2)	(3)	(4)	(5)
	$ln(Pump)$	$ln(Pump)$	$ln(Pump)$	$ln(Pump)$	$ln(Pump)$
$ln(RAC)$	-0.131***	-0.164***	-0.158***	-0.155***	-0.236***
	(0.046)	(0.046)	(0.054)	(0.055)	(0.062)
$ln(Rate_{Canal})$	-0.218***	-0.228***	-0.218***	-0.216***	0.102
	(0.075)	(0.065)	(0.060)	(0.061)	(0.127)
$ln(Recharge)$				-0.002	0.092
				(0.010)	(0.060)
N	55,171	55,171	55,171	55,171	22,999
R^2	0.665	0.695	0.697	0.697	0.694
Well FE	Yes	Yes	Yes	Yes	Yes
Month-of-year FE	No	Yes	Yes	Yes	Yes
Aggregate Shocks	No	No	Yes	Yes	Yes

Notes: Results are reported from an OLS regression with fixed effects. The dependent variable is the natural log of groundwater extraction for well i in month t. Standard errors clustered at the well and region-year are in parentheses. *,**,*** denote significance at the 10%, 5%, and 1% level. Aggregate shocks include the log of monthly district-level surface water use, monthly weather controls, and annual SWP deliveries.

Table 8 reports results from the estimation of modified versions of equations (1) and (2), in which we condition on surface water rates in all specifications. The columns in this table mirror those reported in Table 2, except importantly, each column also includes surface water prices as a control. We continue to find that an increase in groundwater prices leads to a modest reduction in groundwater use, though relative to our results in Table 2, demand for groundwater is slightly more inelastic. These results also demonstrate that an increase in district-wide surface water prices reduces demand for groundwater, with price elasticity estimates hovering around -0.22. A negative effect of surface water prices on groundwater use would suggest that surface water prices partly reflect groundwater prices, and that this relationship dominates the substitute good channel. In sum, we find that the qualitative relationship between groundwater prices and groundwater demand is robust to surface water supplies.

B Appendix: Price Elasticities of Water Demand

We conducted a review of all the empirical estimates of the demand elasticity for agricultural water published since the Scheierling et al. (2006) review paper to highlight differences in interpretation across estimates due to differences in empirical strategies, price levels, price variation and other notable features.

In summary, many factors influence the magnitude of the point estimate of the price elasticity of agricultural demand, and these vary across studies. Micro-level, fixed-effects estimates exist in the literature but differ from ours along important dimensions. For example, both Gonzalez-Alvarez, Keeler, and Mullen (2006) and Hendricks and Peterson (2012) deploy fixed effects models and focus exclusively on groundwater-only farms, but their settings (Georgia and Kansas) feature different environmental conditions and different price variation. These studies lack direct measures of water price and instead proxy for pumping costs as a function of well or groundwater depth and fuel prices. According to Mieno and Brozovič (2017), the imputation of marginal water prices can cause attenuation or amplification bias, depending on the empirical strategy deployed and the way costs are estimated. Schoengold, Sunding, and Moreno (2006), on the other hand, focus exclusively on surface water-only users and estimate demand as a function of water rates, crop and technology choices and directly observable farm-level characteristics using GLS. They assume water rates are exogenous, but instrument for endogenous technology and output choices. We argue that, absent experimental variation in water prices, two-way fixed effects models are a better approach for credibly isolating the short-run impact of water prices on demand because they more flexibly control for unobservable characteristics that may confound estimation. While these fixed-effects models may not allow for identification of effects that are constant over time or across fields, this is not the objective in the case of estimating a price elasticity.

Wheeler at al. (2008) and Hagerty (2019) are the only two studies to utilize market transaction data from Australia and California, respectively, with Hagerty's estimate being at the wholesale level and thus more challenging to compare. Both use instrumental variables techniques to overcome the classic endogeneity concerns due to simultaneously determined market outcomes. Most similar to our study is the Smith et al. (2017) paper which also exploits a directly observable, albeit self-imposed, groundwater tax. The authors deploy a difference-in-difference approach with parcel and time fixed effects. Notable differences between their estimate and ours include the time frequency of the data, the crops being produced in the region, and the inclusion of a constant to account for the energy costs of extraction. In stark contrast to the Coachella Valley, the San Luis Valley in Colorado features lower value field crops like alfalfa, pasture, potato, and other grains. Smith et al. (2017) apply an average pumping cost of $40/AF to all wells in their data. To explore the directional effects of these differences, we confirm that (1) the elasticity estimate we derive from a difference-in-difference approach (with parcel and time-fixed effects) in Section 5.1 and (2) the implied elasticity after adding energy extraction costs of $16/AF to all wells in our data result in elasticity estimates that are larger in absolute value than our main estimate of -.17.

All estimates since Scheierling et al. (2006) tend to be more elastic than our estimate; they range from -0.1 to -0.79 and average -0.45. Unlike ours, all studies use annual data, which would partially explain why other estimates tend to be larger. In fact, when we collapse our data to the annual level, we estimate a slightly more elastic estimate of -.24. Other factors influencing the magnitude include the level of prices that farmers face, the crops grown, rainfall and other environmental factors, and the potential for surface-groundwater substitution. When conjunctive use of surface and groundwater is possible, demand for groundwater should be more elastic to changes in groundwater pumping costs than when groundwater is the only source. Also, at low prices demand is very inelastic. While we do not consider prices in the Coachella Valley to be low, the fact that conjunctive use is possible, and that farmers grow high-value specialty crops, may partially explain our inelastic estimate.

Similarly, Table B summarizes four empirical estimates of the demand elasticity for residential water. The tables makes note of important differences in empirical strategies, price levels, price variation and other features that may affect the magnitude of the elasticity estimates.

Table 9: Review of Empirical Demand Elasticity Estimates for Agricultural Water

Paper	**Estimate**	**Empirical Approach; Price Measure & Levels; Setting**
Scheierling et al. (2006)	-0.48	Meta-analysis/review paper that reports average of previous estimates. Studies differ in what other inputs are being held constant, water demand is more elastic at higher prices, range of prices and time frame, mix of crops, climate.
Gonzalez-Alvarez, Keeler, Mullen (2006)	-0.27	Fixed-effects model with four years of annual data. Authors estimate marginal pumping costs as a function of well depth, pump type, fuel price. Mean pumping cost is equal to $21.54 per AF (1999 dollars). Crops: forage, sweet corn, tomato, sod. Farms with groundwater only. Georgia, USA.
Schoengold, Sunding, Moreno (2006)	-0.79	Estimate water demand as a function of output and technology choices, prices, and other environmental characteristics with a panel GLS model that allows for heteroscedasticity. Use IV to account for endogeneity of technology and output choices in water demand. Prices range from $46.7-53 per 1000 cubic meter. Focus exclusively on farms with surface water only. Southern California, USA.
Wheeler et al. (2008)	-0.52	Using bid prices for demand and supply of water allocations and average monthly prices paid for water allocations to sketch out demand along bid curve. Yearly data on volumes traded, and monthly average prices paid. Australia.
Hendricks and Peterson (2012)	-0.1	Estimate two-way fixed effects model with annual field-level panel data spanning 16 years. Cost of pumping changes due to energy prices and differences in depth to water. Crops: corn, sorghum, alfalfa, wheat, soybean. Average price is $9.60 per acre-foot. Focus on groundwater only users. Kansas, USA.
Smith et al. (2017)	-0.77	Exploit a directly observable price instrument. Difference-in-difference on treated regions after 2011 with fixed effects and five years of annual data. Pumping fee in treated regions is $45/AF in 2011 and $75/AF in 2012. Crops: alfalfa, pasture, potato, grains, other. Proxy for groundwater costs with depth (annual avg that masks intra-year variation) and no knowledge on utility provider and pump efficiency. Apply an average pumping cost to all wells within the estimated range, settling on $40 per AF. Assumes all variation in pumping comes from fee. Colorado, USA.
Hagerty (2019)	-.23	Uses annual market transaction data to estimate wholesale (irrigation district level) elasticities. Exploits historical allocation rules in California. Estimates inverse demand functions P(Q) and instruments for quantities using yearly water entitlements, which are plausibly exogeneous because they are based on weather fluctuations and historically determined allocations. California, USA.

Notes: Table is not comprehensive. Many factors influence the magnitude of the point estimate of the price elasticity of agricultural demand, including but not limited to surface-groundwater substitution availability; crop type, agricultural production and irrigation technology; rainfall and other environmental factors; time frequency of data and whether water use data consist of aggregate or micro-level observations, and the magnitude of the price levels.

Table 10: Empirical Demand Elasticity Estimates for Urban Water

Paper	**Estimate**	**Empirical Approach; Price Structure; Setting**
Nataraj and Hanemann (2011)	-.12	Exploit the introduction of a third price block in an increasing block pricing schedule for water using bi-monthly data. Regression discontinuity approach tests if consumers respond to marginal prices. Limited to high-use/high-income households. Santa Cruz, CA, USA.
Baerenklau et al. (2014)	-0.76	Calculate the demand effects of a water budget rate structure change from uniform to a fiscally neutral increasing block rate structure. Authors use monthly household data to estimate a fixed-effects model for the period with a uniform water rate. Predicted demand from this model is compared to realized demand under the period with water budget pricing. Riverside, CA, USA.
Wichman (2014)	-.43 to -1.14	Exploit rate structure change to estimate elasticities with respect to perceived prices. Uses triple difference design to estimate impact across distribution of consumption. Chapel Hill, North Carolina, USA.
Brent and Ward (2019)	-.13	Randomized field experiment of single family homeowners. Survey elicits information about prices that households perceive. They assess the impact of accurate price information on consumption. Melbourne, Australia.

Notes: Table is not comprehensive. We highlight four empirical estimates that have been published recently. Elasticities may vary across studies due to differences in underlying tariff regimes, variation in income across regions studied, and other differences in the research design (Dalhuisen et al. 2003).

C Appendix: Simulation Details

Herein we provide details on the estimation of baseline agricultural and urban prices used in the market simulation, as well as the explicit analytical expressions for relevant surplus measures.

C.1 Agricultural Price

To calculate the price for agricultural groundwater that corresponds to the baseline quantity, x_A^0, 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 in 2016, which amounts to \$84.60/AF. To impute the average energy cost per acre-foot of water, we follow a well-known engineering formula presented by Rogers and Alam (2006) that translates the depth to the water table and energy prices to an average per AF energy cost of extraction.

The full per-unit price of an AF of groundwater in time t is given by $P_t = \phi p_t^e h_t + P_{RAC,t}$, where $P_{RAC,t}$ is the volumetric price of groundwater per AF, h_t represents the height of the water table, p_t^e is the energy price, and ϕ is the energy requirement to raise an AF of water up one foot (Rogers and Alam, 2006). Following Rogers and Alam (2006), we assume the kwh requirement to lift 1 AF of water 1 foot is $\phi = 1.551$.[27] Mean depth to the water table was calculated by averaging the depths in 2016 across the 10 active irrigation wells in the Coachella Valley Indio subbasin that are monitored and reported to the California Statewide Groundwater Elevation Monitoring (CASGEM) program. With an average depth to the water table of 108 feet, and the price per kWh of energy for agricultural users in Coachella in 2016 of \$.0952/kWh:

$$P_t = (1.551) * (\$0.0952) * 108ft + \$84.60 = \$100.50. \tag{7}$$

For our market simulation, the imputed price of groundwater is \$100.50 per AF, and the

[27] The constant $\phi = 1.551$ accounts for pump efficiency by assuming an electric pump output of 0.885 water hoursepower-hour per kwh (Rogers and Alam 2006).

quantity of agricultural groundwater consumption corresponding to this price is 233,219 AF.

C.2 Urban Price

We try several approaches to estimating the relevant marginal cost for urban users. California Water Code Section 10608.34 requires urban retail water suppliers to conduct and submit validated water loss audit reports to the Department of Water Resources on October 1, annually.[28] These include reported costs to produce and supply the next unit of water, i.e., variable costs of procuring and producing water. The cost is determined by calculating the summed unit costs for treatment and all power used for pumping from the source to the customer. It may also include other miscellaneous costs that apply to the production of drinking water and it should also include the unit cost of bulk water purchased as an import if applicable. In the CVWD, treatment costs are just 7% of CVWD's operation and maintenance budget. For fiscal year 2016/17, CVWD reported a variable production cost of $717.20 per million gallons, which translates to $233.70 per AF. Even though this number likely contains costs associated with water treatment, it is reasonable to assume that it is close to the relevant marginal cost.

The district also reports a "Customer Retail Unit Cost" which represents the charge that customers pay for water service. Since the utility has a rate structure that includes a variety of different costs based upon class of customer, a weighted average of individual costs and number of customer accounts in each class can be calculated to determine a single composite cost that should be entered into this cell. CVWD reported $1.54/ccf, which translates to $671.25/AF.

A final approach is to measure the average per-unit retail price by taking advantage of observed data on total water use per budget-based tier and category (single, multi-family unit) in 2016. We match this with rate schedules that publish the tiered pricing structure for each category including the quantities of water that fall within each tier, the marginal price in each tier and the monthly meter service charge (CVWD 2016b). We then calculate for the year the average price per AF of water. We measure an average

[28]The data are available at https://wuedata.water.ca.gov/awwa_plans.

price per acre-foot of \$721.13, or \$1.66 when measured in ccf, a price that is close to that reported by Baerenklau et al. (2014).

C.3 Surplus Measures

We measure the cost of a 25% urban cut-back by calculating the area under the urban water demand curve above c_U between the constrained quantity ($(1-.25)x_U^0$) and the status quo quantity (x_U^0):

$$DWL = \int_{(1-.25)x_U^0}^{x_U^0} \Big((\frac{\tau}{\gamma_U})^{-\frac{1}{\eta_U}} - c_U \Big) d\tau, \tag{8}$$

$$DWL = \frac{\gamma_U}{1-\frac{1}{\eta_U}} \left[(\frac{x_U^0}{\gamma_U})^{(1-\frac{1}{\eta_U})} - (\frac{(1-.25)x_U^0}{\gamma_U})^{(1-\frac{1}{\eta_U})} \right] - c_U x_U^0 + (1-.25)c_U x_U^0. \tag{9}$$

This area is illustrated in Figure A.1 for endowment E_U and baseline price denoted by c. Similarly, we can measure the cost of a z% cut-back to both agricultural and urban users:

$$DWL(z) = \int_{z(x_U^0)}^{x_U^0} \Big((\frac{\tau}{\gamma_U})^{-\frac{1}{\eta_U}} - c_U \Big) d\tau + \int_{z(x_A^0)}^{x_A^0} \Big((\frac{\tau}{\gamma_A})^{-\frac{1}{\eta_A}} - c_A \Big) d\tau, \tag{10}$$

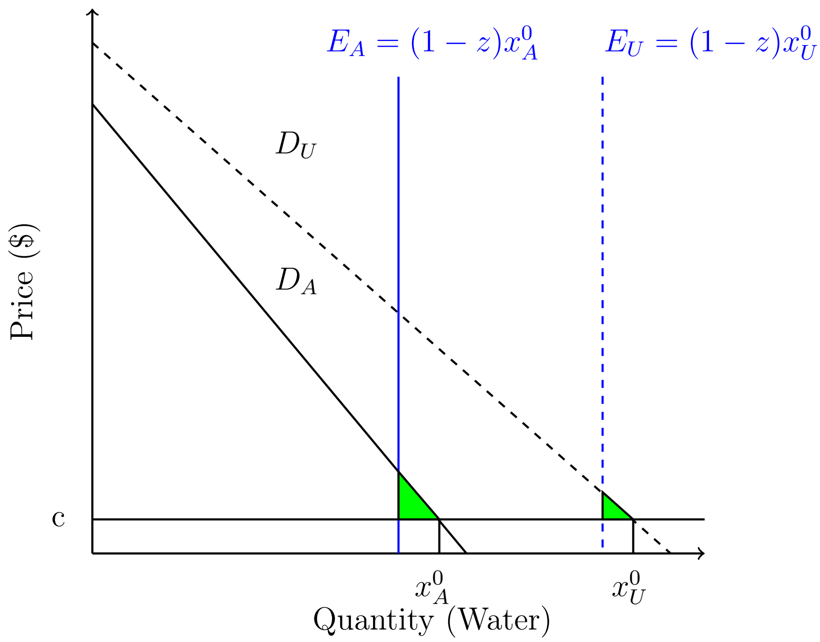
$$DWL(z) = \frac{\gamma_U}{1-\frac{1}{\eta_U}} \left[(\frac{x_U^0}{\gamma_U})^{(1-\frac{1}{\eta_U})} - (\frac{(1-.z)x_U^0}{\gamma_U})^{(1-\frac{1}{\eta_U})} \right] - c_U x_U^0 + (1-z)c_U x_U^0 + ... \tag{11}$$
$$\frac{\gamma_A}{1-\frac{1}{\eta_A}} \left[(\frac{x_A^0}{\gamma_A})^{(1-\frac{1}{\eta_A})} - (\frac{(1-z)x_A^0}{\gamma_A})^{(1-\frac{1}{\eta_A})} \right] - c_A x_A^0 + (1-z)c_A x_A^0.$$

In Figure 8, we express the gains from trade (equation 5) as a fraction of this DWL:

$$\%\triangle = \frac{DWL_U(z) - DWL_T(z)}{DWL_U(z)} * 100 = \frac{G(z)}{DWL_U(z)} * 100. \tag{12}$$

$DWL_U(z)$ is the deadweight loss of a uniform standard and $DWL_T(z)$ is the deadweight loss of a curtailment in the presence of trade. Their difference represents the gains from trade. Expressed as a percentage change of the deadweight loss of a uniform standard, we can interpret this as the percentage change in surplus due to the presence of trade,

Figure A.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^0 for $i \in A, U$ denote the unconstrained quantities of water demanded and E_i represents water allocations under a water supply reduction of z% to each user type.

i.e., the extent to which trade can reduce the cost of a uniform water supply curtailment. With larger values of z, the deadweight loss from a uniform reduction in water availability becomes greater as the difference in the marginal willingness-to-pay across sectors is exacerbated.