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Using Price Elasticities of Water Demand to Inform Policy

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Abstract

This survey distills recent work on the price elasticity of demand for urban and agricultural water and outlines how it can inform the design of market-based approaches to manage increasingly scarce water resources. We offer a brief description of the water sector, including the primary users, main water sources, and market failures in the allocation and use of surface water and groundwater. A review of recent empirical research on the price elasticities of agricultural and urban water demand shows the progress made in our understanding of user response to prices and reveals substantial heterogeneity in the price response. We apply what we have learned about elasticities to surface water markets and price-based groundwater management. Heterogeneity in price elasticities suggests that water transfers may lead to large efficiency gains, but that their magnitude is site specific. Groundwater pricing may cost-effectively manage groundwater and fund the development of alternative water supplies, but heterogeneity in elasticity estimates highlights that the conservation and revenue generated are basin specific.

1. INTRODUCTION

The American West has a long history of coping with periods of extreme drought and adjusting to swings between surface water scarcity and excess. This endemic variability in precipitation and temperature has resulted in the diversion of rivers, the construction of dams and reservoirs, the passage of large water projects, and the drilling of wells. These supply-side strategies redefined water availability in the West, supplying water to water-scarce regions, making it available during times of drought, and storing it during times of plenty. Demand-side approaches to reallocate water or induce conservation have been less frequently deployed.

Climate change models project warming temperatures, increased variability in precipitation patterns, and more frequent and extreme weather events (Kunkel et al. 2013, Swain et al. 2018). In California, warmer temperatures imply that less precipitation will fall as snow and more as rain; the existing snowpack will melt earlier and alter when surface water supplies are available; and evaporation rates will increase (Jessoe et al. 2020). Droughts and flooding are expected to occur more frequently and with increased severity. Forecasts indicate that these changes will translate into reductions in surface water supplies and increased demand for groundwater. Market-based approaches that price water to encourage conservation during times of scarcity and allow for transfers across users can mitigate the costs of drought and climate change.

In this article, we provide an overview of the potential for water pricing and markets to manage surface and groundwater supplies, with a focus on the American West.[1] We begin by describing the water setting: the main sources of supply, the primary consumers, and the institutional features that lead to market failures in the allocation and consumption of water. Next, we review recent literature that brings an empirical focus to the long-standing question of the price elasticity of demand for water. Informed by this literature, we then discuss the role that water transfers and pricing could play in reducing existing allocative inefficiencies and mitigating the costs of reductions in water supplies.

The regulatory landscape governing property rights and pricing for water has contributed to the overconsumption and misallocation of water across users. The primary nonenvironmental consumers of water are agricultural and urban users, with the former accounting for roughly 40% of water use nationwide. The main sources of water in the West are surface water—water bodies such as rivers, streams or lakes—and groundwater—water that can be extracted from underground aquifers. One mismatch between demand and supply arises from the largely nontransferable property rights governing surface water and the general absence of property rights for groundwater. Surface water is rarely allocated to those with the highest willingness to pay, and groundwater overextraction occurs. Additional inefficiencies stem from water prices that rarely reflect marginal costs and frictions that prevent welfare-improving transfers. Improvements in water pricing and transfers may address some of the existing imbalances between supply and demand.

A growing body of literature has used panel data and quasi-experimental approaches to improve our understanding of the price elasticity of demand for agricultural and urban water. In the urban setting, we report substantial heterogeneity in the price response. The majority of this work confirms earlier findings that demand is relatively insensitive to price but points to new reasons as to why. Complex pricing schemes, misperceptions about consumption quantities, and nonsalient prices offer new insights into the possible reasons for inelastic demand. In the agricultural setting,

[1]Water scarcity and issues regarding the allocation of water resources extend beyond the American West. Arid and semiarid regions around the world, including Australia and Israel, face extreme water scarcity and stand to gain from well-designed market-based instruments that effectively manage scarce water resources.

a new wave of empirical literature has brought more credible empirical estimates on the price elasticity of demand for surface and groundwater. These estimates highlight substantial heterogeneity in agricultural price elasticities and highlight the sensitivity of results to the water source, measure of price, features of agricultural production, climate, and availability of substitute supplies.

Differences across urban and agricultural elasticities highlight that water trading could reduce existing allocative inefficiencies. Drawing from the literature on property rights, transaction costs, and elasticities in the water setting, we highlight some impediments to the deployment of water markets and the potential gains from their establishment. The heterogeneity revealed in our elasticity review underscores that gains from surface trades will differ across sites. We also apply findings from our review to understanding price-based groundwater management. Groundwater pricing presents a cost-effective strategy for reducing groundwater use or for generating revenue to fund other basin management activities. However, substantial variation in elasticity estimates across settings highlights that the conservation and revenue generated from a groundwater tax will be location specific.

Market failures in the management of water resources are a pressing but expansive topic and one that is not exhaustively covered in this overview. We restrict our attention primarily to the question of the price elasticity of demand for water and the role this measure brings to surface water markets and groundwater pricing. In doing so, we forgo a discussion of a number of relevant, related, and important topics on the management of water. These include the role of nonprice water conservation instruments, commercial and industrial water use, interactions with the environment, and instruments to manage water quality. Keiser & Shapiro (2019), Kroetz et al. (2020), and Pérez-Blanco et al. (2020) provide recent syntheses on some of these topics for the interested reader.

2. WATER SUPPLY AND DEMAND

In the United States, urban areas, agriculture, and thermal electric power plants are the main water users. In 2015, irrigation represented 37% of water withdrawals, public supply constituted 12% (municipal, industrial, and commercial combined), and thermoelectric power for generating electricity accounted for 41% of US water use (Dieter et al. 2018). There is substantial spatial heterogeneity in this statistic. For example, in California, agriculture and urban use account for roughly 80% and 20% of water use, respectively.

Freshwater comes from two primary sources: groundwater and surface water. In 2015, groundwater constituted 26% of the water supply in the United States, but it plays a much larger role during times of drought and in regions without surface water access.[2] In much of the West, imported surface water supplies are as important, if not more, than local surface water supplies. In California, snow and rain occur mostly between November and April and mainly in the mountainous north, which is different in both space and time from where crops are grown. Reservoirs, aquifers, and snowpack are critical for shifting when water can be used, allowing winter precipitation to be accessed during the long annual dry months that last from roughly May through October. Groundwater provides a stored source of water that becomes increasingly important and relied upon during periods of drought.

While fundamentally the same interconnected resource, we treat, manage, and regulate surface water and groundwater differently. Each is governed with different allocation rules, characterized by distinct externalities, and displays different dynamics. We now articulate why features of the

[2] Here, water supply refers only to water withdrawn from a river, lake, reservoir, or well.

water setting introduce market failures and discuss the economics literature on this topic. We do this separately for groundwater and surface water.

2.1. Groundwater Governance and Market Failures

Groundwater often lacks well-established property rights and for this reason exhibits the classic problems of a common-pool resource (Gordon 1954, Hardin 1968). Consumption is rival and nonexcludable, and a market failure occurs because one user's consumption imposes costs on others. Extraction today imposes a stock externality by reducing the supply available for tomorrow's user. It may introduce a spatial pumping cost externality if consumption draws down the water table and increases pumping costs for others nearby (Brozović et al. 2010, Pfeiffer & Lin 2012, Edwards 2016). Pumping may cause a quality externality if extraction exacerbates saltwater intrusion or increases the concentration of natural or anthropogenic contaminants in the remaining groundwater stock. It may also cause land subsidence or spatial environmental externalities (Kuwayama & Brozović 2013).

The Coasian prescription to this dilemma is to introduce well-defined and tradeable property rights (Coase 1960, Anderson & Libecap 2014). In the presence of low transaction costs and well-defined property rights, optimizing resource owners can negotiate and arrive at an optimal quantity of groundwater extraction. Recent work brings empirical support to this insight, demonstrating that the introduction of property rights reduces extraction efforts in groundwater and other environmental settings (Birkenbach et al. 2017, Hsueh 2017, Ayres et al. 2018, Costello & Grainger 2018, Drysdale & Hendricks 2018). Ayres et al. (2021) find that land values in California increase with the establishment of transferable property rights for groundwater, suggesting that well-defined property rights can generate sizable net benefits. However, in some groundwater settings transaction costs may be large and property rights difficult to define.

In the absence of well-defined property rights and in the presence of sizable transaction costs, a tax could correct for consumption externalities (Pigou 1932, Baumol & Oates 1988). As a first step, a large theoretical and more recent empirical literature has sought to formalize and quantify stock and spatial externalities from groundwater pumping (Provencher & Burt 1993). This work has produced mixed results. The seminal Gisser-Sanchez result points to small stock externalities and hence small differences in welfare between open-access and optimal groundwater extraction (Gisser & Sanchez 1980, Brill & Burness 1994, Koundouri 2004).[3] More recently, the literature has focused on quantifying the spatial externality and finds substantial welfare gains from the optimal management of groundwater resources (Brozović et al. 2010, Pfeiffer & Lin 2012, Edwards 2016, Merrill & Guilfoos 2017). Although significant progress has been made on the magnitude and heterogeneity of stock and spatial externalities, quality externalities have received comparatively less attention in the literature (Roseta-Palma 2002). Water quality may be the binding constraint to future groundwater availability.

As a whole, the literature demonstrates that groundwater externalities, as well as their optimal taxation remedies, are dynamic in nature and vary based on site-specific features. Groundwater is typically modeled as a dynamic resource, and the optimal extraction path depends on the rate of replenishment in the aquifer, the depth to the water table, and drought conditions. Local aquifer and basin characteristics also determine the type of pumping externalities, the volume of storage, and potential welfare gains from management (Edwards 2016, Lin Lawell 2016). Less

[3] Koundouri (2004) provides an overview, and finds that, with the exception of one study, welfare gains from management are small, averaging 5.8%.

well understood is how users would respond to a groundwater price. This depends on the price elasticity of demand for water, which is the focus of Sections 3.1 and 3.2.

2.2. Surface Water Governance and Market Failures

An important foundation in the distribution and consumption of surface water is the legal framework delineating the assignment of property rights. Surface water is governed by a legal system comprised of riparian rights, appropriative rights, or some combination of the two (Shaw 2007). The Riparian Doctrine, which allows reasonable use by a person whose land borders a body of water, determines rights for surface water in much of the Eastern United States. In much of the Western United States, water rights are governed by the "first-in-time, first-in-right" Doctrine of Prior Appropriation, or by a mix of riparian and appropriative rights. Arizona, Colorado, Montana, Nevada, New Mexico, Utah, Wyoming, and Idaho feature a strict interpretation of prior appropriation, referred to as the Colorado Doctrine (Shaw 2007). Ten states, including California and Oregon, have a mixture of Riparian and Prior Appropriation referred to as the California Doctrine. The remaining western states rely exclusively on riparian rights (Shaw 2007). These fixed surface water rights determine allocations of water across individuals, often via wholesalers like an irrigation district, irrespective of their willingness to pay.

Allocative inefficiencies arise not because of the initial distribution of water rights, but because water transfers are difficult, if not impossible, to negotiate and implement (Libecap 2008).[4] In the West, urban and agricultural users often face very different prices for water. Water markets that would allow for transfers among agricultural users or between agricultural and urban or environmental users would allocate water based on willingness to pay. However, transaction costs involved with trades are often prohibitively high, hindering otherwise beneficial transfers (Womble & Hanemann 2020). Some impediments to trade are bureaucratic or political and point to the removal or reduction of these costs as a means to increase transfers and reduce allocative inefficiencies (Libecap 2008, Regnacq et al. 2016). These costs may be exacerbated during times of drought, when lower-priority rights holders face curtailments or are denied water, regardless of the value they attach to water.

The magnitude of the gains from water transfers, both in the absence and presence of drought, will depend on the price elasticity of water demand. To understand the welfare impacts of market-based policies and their relative effectiveness across sectors, we review recent empirical work on the price elasticity of demand for agricultural and urban use and then compare elasticity estimates across these users.

3. PRICE ELASTICITY OF WATER DEMAND

A key parameter in the evaluation of water policies, including but not limited to those seeking to address the market failures raised earlier, is the price elasticity of demand for water. This parameter informs estimates of the welfare impacts of drought mandates, such as the one urban users experienced in California during the 2015 drought (Buck et al. 2016). It informs the role prices and markets can play in meeting groundwater conservation policies, such as the sustainability targets developing under the Sustainable Groundwater Management Act of 2014 (Bruno & Sexton 2020). It speaks to the efficiency gains from surface water transfers that would allow for trading among

[4]An additional inefficiency stems from how wholesalers distribute water among individual users. Water charges are often based on the cost of service, reflecting the capital and maintenance costs of a delivery system. This often results in prices to irrigators that fall below the social marginal cost of water.

agricultural users or between agricultural and urban users (Hagerty 2019). And it can be used to determine the reduction in groundwater extraction that would occur in response to a tax on pumping externalities (Bruno & Jessoe 2021). Collectively, credible estimation of price elasticity estimates will factor into the design of policies to adapt to climate-induced changes in water supplies.

We take as our starting point Dalhuisen et al. (2003) and Scheierling et al. (2006), who offer stand-alone overviews on the price elasticity of demand for urban and agricultural water, respectively, and review the literature that has emerged since their publication. Our literature review focuses on a curated list of empirical estimates of the price elasticity using panel data and documents differences across studies in context, data, and estimation. We also discuss new themes and insights that emerge collectively from this literature.

3.1. Urban Price Elasticity of Water Demand

Residential water is arguably the most regulated segment of the water sector and certainly the most studied in empirical economics (Espey et al. 1997). The latter is partly a result of the availability of disaggregate and longitudinal data on water use, when compared to the agricultural sector. The most recent meta-analysis on the price elasticity of demand for urban water surveys the robust literature on the topic and reports a mean elasticity of −0.41 (Dalhuisen et al. 2003). However, the literature has evolved since this publication, making use of rich panels of billing or high-frequency water-use data, deploying quasi-experimental methods, and asking how a number of factors aside from price impact demand.

Table 1 summarizes the urban price elasticity estimates discussed in this overview, including the citation, the estimated elasticity, and notable features of the setting. The estimated elasticities in this suite of work are heterogeneous, with the bulk of estimates ranging between −0.10 and −0.76. The majority of these studies make use of account-level panel data on water use and deploy approaches that control for selection on fixed unobservables or aggregate time-varying unobservables. Importantly, this body of work takes seriously the complicated nature of many water pricing structures. Olmstead et al. (2007) and Olmstead (2009) formalize the simultaneity concern that arises in tiered pricing structures when the customer's choice of quantity determines

Table 1 Demand elasticity estimates for residential water

Reference	Estimate	Notable features
Dalhuisen et al. (2003)	−0.41	Meta-analysis of previous estimates from the United States
Olmstead et al. (2007)	−0.34	Households span 11 regions with tiered and uniform pricing in the United States, Canada
Nataraj & Hanemann (2011)	−0.12	New pricing tier in Santa Cruz, California
Mansur & Olmstead (2012)	−0.36	Indoor and outdoor demand with households from 11 regions in the United States, Canada
Baerenklau et al. (2014)	−0.76	Uniform price changes in Riverside, California
Wichman (2014)	−0.43 to −1.14	Rate structure change in Chapel Hill, North Carolina
Klaiber et al. (2014)	−0.13 to −1.93	Estimates by season and use, Phoenix, Arizona
Yoo et al. (2014)	−0.66	Census tracts, short- and long-run, Phoenix, Arizona
Wichman et al. (2016)	−0.15 to −0.30	Household use and price variation in 11 municipalities in North Carolina
Buck et al. (2016)	−0.15	Utility level data from 53 urban utilities in California
Brent (2018)	−0.2 to −0.3	Outdoor water use in Phoenix, Arizona
Clarke et al. (2017)	−0.08 to −0.37	Monthly elasticities in Tucson, Arizona
Browne et al. (2021)	−0.16 to −0.39	Rate changes in Fresno, California

their marginal price. Wichman et al. (2016) address this simultaneity concern and go one step further by estimating price elasticities using both average and marginal prices. When faced with complex tiered pricing structures, customers may respond to average prices as opposed to marginal prices (Ito 2014, Wichman 2014, Clarke et al. 2017, Browne et al. 2021). Moving forward, studies must account for simultaneity concerns introduced with tiered and budget-based pricing structures, accurately model the prices to which customers respond, and control for time-varying and unit-level unobservables that impact demand and are correlated with prices. Readers should be cautious when interpreting elasticity estimates that forgo these considerations.

Substantial heterogeneity in the estimated elasticities across studies partly reflects differences in the pricing structures and identifying variation that are at the empirical core of each study. Some estimates lean on changes in rate structures; others use price changes within an existing price structure; others rely on modifications to the existing price structure; and one study exploits changes in perceived prices. For example, in Nataraj & Hanemann's (2011) article, the introduction of a new pricing tier gives rise to a regression discontinuity research design that allows for the estimation of the price elasticity of demand. Wichman (2014) uses the introduction of increased block pricing to estimate the price elasticity of demand. A suite of elasticity estimates that exploit fundamentally different variation in water prices offers advantages and limitations.

A parallel literature since the publication by Dalhuisen et al. (2003) has examined the roles that behavioral biases and information gaps play in understanding the price response in the residential water and electricity settings. Collectively, these studies use experimental or quasi-experimental research designs to highlight that relatively inelastic demand may occur because bills are not salient, customers are misinformed about the quantities because demand for electricity and water are often derived, or users misperceive prices (Ito 2014, Jessoe & Rapson 2014, Wichman 2014, Sexton 2015, Brent & Ward 2019). This literature complements the price elasticity studies that are the focus of this review and offers some possible explanations for the relatively inelastic price elasticities reported in **Table 1**.

This literature review points to some underlying reasons why the elasticity estimates obtained from, for example, the introduction of a new pricing tier for water, as discussed by Nataraj & Hanemann (2011), are not directly comparable to those obtained from price changes within a uniform pricing structure as reported by Baerenklau et al. (2014) and Browne et al. (2021). In the former study, the introduction of a new tier may make prices more salient, and households may be responding to both the price change and new tier. For this reason, even after holding constant the setting, time period, and research designs, discrepancies across price elasticity estimates will likely exist. This mix of elasticity estimates carries with it some distinct advantages, particularly for water regulators and water managers. Utilities have at their disposal data points on the response to new tiers and new rate structures and to changes in marginal prices and changes in average prices, and these will inform new tariffs and tariff structures proposed by agencies.

The location, time dimension, and demographics of the empirical setting also likely explain why we observe a range of elasticities. The response to prices likely differs between arid Arizona and relatively higher precipitation locations because of differences in climate (Yoo et al. 2014). Timing also matters. One would expect the response to differ across seasons and during times of drought (Klaiber et al. 2014, Clarke et al. 2017), and demand is likely to be more elastic in the long run, when households can alter landscaping choices and durable good purchases, than in the short run (Yoo et al. 2014, Brent 2018). Income, lot size, baseline water use, and household size also influence the response, with higher-income households and indoor water use being less sensitive to price changes (Olmstead et al. 2007, Nataraj & Hanemann 2011, Mansur & Olmstead 2012, Klaiber et al. 2014, Wichman et al. 2016, Brent 2018). How these demand shifters influence the price elasticity is important for understanding the potential of price as an urban water-management tool.

Table 2 Demand elasticity estimates for agricultural water

Reference	Estimate	Notable features
Scheierling et al. (2006)	−0.48	Meta-analysis of previous estimates from the United States
Gonzalez-Alvarez et al. (2006)	−0.27	Estimate with energy prices and depth to groundwater, Georgia
Schoengold et al. (2006)	−0.79	Surface water only, Southern California
Wheeler et al. (2008)	−0.52	Market transactions, Australia
Hendricks & Peterson (2012)	−0.10	Estimate with energy prices and depth to groundwater; groundwater users only, Kansas
Smith et al. (2017)	−0.77	Self-imposed tax, San Luis Valley, Colorado
Hagerty (2019)	−0.23	Wholesale level from surface water market, California
Burlig et al. (2020)	−1.12	Energy prices, California
Bruno & Jessoe (2021)	−0.15	Volumetric pumping price, Coachella Valley, California

3.2. Agricultural Price Elasticity of Water Demand

A recent body of research has returned to the long-standing question of the price elasticity of demand for agricultural water, armed with panel data that allow for the deployment of quasi-experimental methods. Compared to the residential water setting, empirical estimation of agricultural elasticities has been hindered by the general absence of data on agricultural water use and water prices. However, credible estimates of this elasticity are essential to the design of policies to address market failures in the water setting and induce conservation during droughts.

Table 2 summarizes work on the price elasticity of agricultural water since the comprehensive meta-analysis of Scheierling et al. (2006). This table reports the estimated elasticity and notable features of the study, including the measure of price, empirical setting, and water source. One insight from this body of work is the variation in estimated elasticities across studies, with estimates ranging from −0.1 up to −1.12. As we detail below, this heterogeneity may be driven by systematic differences in water sources, the measurement of price, and the agricultural contexts across studies.

A first key distinction is the choice to focus on groundwater or surface water. While these two goods are typically modeled as perfect substitutes, as discussed earlier, the regulatory framework governing the management of each is unique. This leads to differences in the price variation used to estimate the price elasticity of demand. Typically, surface water estimates exploit observed market transactions or observed variation in water rates. Schoengold et al. (2006) use generalized least squares to estimate demand as a function of surface water rates and other observables and assume that, conditional on observables, water rates are independent of potential outcomes. Actual market transactions provide price variation in other studies and allow for the estimation of farm-level or wholesale surface water price elasticities (Wheeler et al. 2008, Hagerty 2019). These studies recognize that market prices and quantities are simultaneously determined and address this with an instrumental variables approach. Collectively, surface water estimates report an elasticity range of −0.23 to −0.79.

In the groundwater setting, water is rarely priced. Economists have a long history of using energy costs, explicitly the cost involved to raise an acre-foot of water from the water table to the surface, to measure groundwater prices. Panel data on groundwater extraction, fuel prices, and water table depths coupled with engineering assumptions have allowed researchers to control for unobservables that may have confounded estimation in earlier work (Pfeiffer & Lin 2014). This is on display in studies by Gonzalez-Alvarez et al. (2006) and Hendricks & Peterson (2012) that lean on panel data and fixed effects models to estimate groundwater price elasticities of −0.27 and −0.10, respectively. Other recent work takes advantage of billing data on electricity use, audits of pump efficiencies, and electricity prices to estimate the price elasticity of demand for electricity. An engineering model then allows for the approximation of groundwater use and estimation of elastic demand for groundwater at −1.12 (Burlig et al. 2020). Even among studies that rely on energy costs to measure groundwater prices, we observe a wide range of elasticities. One reason for this may be that the imputation of marginal water prices can cause attenuation or amplification bias, depending on the empirical strategy deployed and the way costs are estimated (Mieno & Brozović 2017).[5]

Though atypical, volumetric pricing for groundwater exists in some water districts. In these settings, pricing was either introduced voluntarily or as a revenue source to fund replenishment or alternative water supplies. Recent work has focused on evaluating the impact of these volumetric groundwater prices on agricultural water use (Yoo et al. 2014, Smith et al. 2017). To estimate the price elasticity of agricultural demand, Bruno & Jessoe (2021) study a water district that charges three distinct geographical volumetric prices for groundwater and collects monthly data on well-level water use. Smith et al. (2017) study the question in the San Luis Valley, Colorado, an area that introduced a self-imposed groundwater tax and collects well-level data on groundwater extraction. Well-level panel data on groundwater extraction and variation in groundwater prices enable each study to estimate difference-in-differences and fixed effects models that control for fixed and time-variant unobservables that may otherwise confound estimation. Even restricting our attention to these similar settings, we continue to find price elasticity estimates varying between −0.15 and −0.77. Differences may occur because of modeling choices, including the elasticity time-step or whether estimates are gross or net energy costs and the magnitude of price changes. As volumetric pricing for agricultural groundwater takes shape in different locations and under various pricing structures, we recommend that researchers take advantage of new opportunities to study the agricultural responses to water pricing.

Heterogeneity in elasticity estimates may arise because of differences in the environmental, agricultural, or regulatory conditions and in data availability on prices. The availability of alternative substitute water supplies will likely influence the price elasticity of demand. As an example, Hendricks & Peterson (2012) rely exclusively on groundwater irrigators, Schoengold et al. (2006) exploit users of surface water only, and Bruno & Jessoe (2021) study farmers with access to both surface water and groundwater. Climatic conditions and weather differ across studies, with the growing conditions in Georgia systematically different from those in Colorado (Gonzalez-Alvarez et al. 2006, Smith et al. 2017). The types of crops grown on land, while themselves an outcome variable, will also influence farmer sensitivity to prices. One might imagine that the response to an increase in prices might be quite different in a location with annual field crops than an area with high-value perennials.

4. IMPLICATIONS OF PRICE ELASTICITIES FOR WATER POLICY

Credible price elasticity estimates operate as essential inputs into assessments of the efficacy of water policies intended to address the previously discussed market failures, encourage conservation, and cope with climate change. In this section, we demonstrate how price elasticity estimates will inform the design of surface water markets aimed at reducing allocative inefficiencies and how elasticities influence market-based approaches that seek to regulate externalities from

[5]When farmers do not face an explicit price for water, irrigation costs are equivalent to the energy costs required to pump the groundwater from below. These energy costs are a function of three factors, all of which are typically measured with error: pumping water levels, pressure head, and pumping efficiency (Mieno & Brozović 2017). If, for example, pumpers that have more efficient pumps tend to be more responsive to changes in energy prices on average, then an imputed water price that assumes uniform pumping efficiency would result in nonclassical measurement error, biasing elasticity estimates.

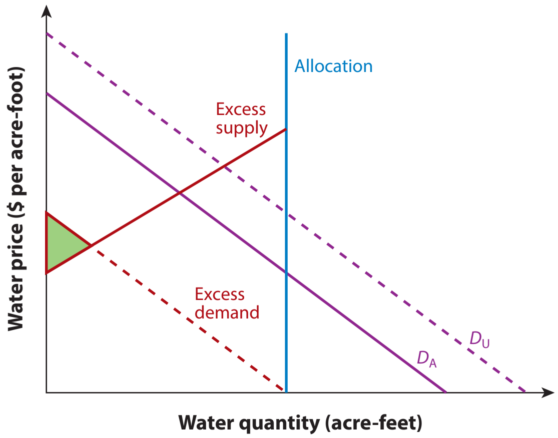

Figure 1

Gains from water trade. The shaded triangle represents the gains from water trade given heterogeneous demand for agricultural and urban water, denoted D_A and D_U, respectively, and an equal allocation across sectors.

groundwater pumping. The latter discussion focuses specifically on how price instruments can factor into the management of groundwater under California's Sustainable Groundwater Management Act.

4.1. Surface Water Trading

As introduced in Section 2.2, the governance and assignment of water rights in the Western United States may lead to allocative inefficiencies. This is because under current regulations, prohibitive transaction costs typically accompany potential water trades. Surface water markets that would allocate water to where it is valued most may lead to substantial welfare gains (Yoo et al. 2014, Regnacq et al. 2016, Donna & Espín-Sánchez 2018, Hagerty 2019). However, as made clear in theoretical, structural, or simulation-based work on water markets, the potential gains from water transfers depend on heterogeneity in willingness to pay across user groups (Vaux & Howitt 1984, Howitt 1994, Hearne & Easter 1997, Sunding et al. 2002, Edwards et al. 2016).

We illustrate this idea in **Figure 1**, which provides a simple stylized illustration of the potential gains from water trade across two user groups. $P = D_U(Q)$ and $P = D_A(Q)$ represent the aggregate demand curves for urban and agricultural users, respectively, where P represents price measured in \$/acre-foot. The vertical line represents an assumed equal allocation of water between the two sectors, $\overline{Q}$, from which excess supply and excess demand curves for a water market are derived; i.e., $P_i = D_i(Q) - \overline{Q}$ for $i \in [U, A]$.[6] The area of the shaded triangle shows the economic benefits from water trade, assuming perfect competition. This figure highlights that the greater the heterogeneity across users in the price elasticity of demand, the larger the gains are from trade. Importantly, the magnitude of the gains from trade is not exclusively a function of the price elasticity. It depends on allocations, market size, and baseline prices, all of which may be difficult to estimate.

[6]At the allocation determined by the vertical line, urban users necessarily have a greater point-price elasticity of demand (in absolute value).

Our survey of the literature highlights substantial heterogeneity both across and within user groups and points to substantial efficiency gains from water trading. As an example, ceteris paribus, water transfers in Southern California using the −0.79 agricultural elasticity reported by Schoengold et al. (2006) and the −0.15 urban elasticity by Buck et al. (2016) would lead to sizable efficiency gains. However, this review of elasticities also makes clear that the gains from a given transfer or local market will be setting specific. This can be seen by simply replacing Buck et al.'s (2016) elasticity with the −0.76 Southern California residential price elasticity estimate reported by Baerenklau et al. (2014). Under this scenario, the gains from trade would be relatively small. Transfers characterized by low transaction costs and large differences in willingness to pay are the most promising and will deliver the largest efficiency gains. More research on heterogeneity in the price elasticity of agricultural surface water use will refine our understanding of the potential of and limits to surface water trading.

Our discussion of water trading has focused exclusively on allocative efficiencies, but well-designed policies must also account for the distributional and environmental implications of water trading. Recent work has started to account for the environmental impacts of connected groundwater and surface water systems (Kuwayama & Brozović 2013), but the question of the distributional impacts of these transfers remains largely unanswered.

4.2. Groundwater Management

In response to declining groundwater resources, groundwater regulations have been taking shape or are being rolled out throughout the American West. In California, the corresponding regulation is the Sustainable Groundwater Management Act of 2014. This landmark regulation, which was in part a response to the most recent drought, requires overdrawn groundwater basins to develop plans to achieve stable groundwater levels by 2040. This fundamentally shifts groundwater from an unmonitored and unregulated open-access resource to a regulated and monitored resource. Importantly, this legislation gives local water districts flexibility in how they reach sustainability targets. Market-based approaches including groundwater pricing and cap-and-trade may offer cost-effective approaches to meet these targets.

The groundwater price that is needed to meet sustainability targets depends on the price elasticity of demand. And as we can see, the reported price elasticity of demand for agricultural groundwater is site and study specific, ranging from −0.1 to −1.1. However, by design, the implementation of the Act is also site specific. To date, more than 250 groundwater sustainability agencies have formed in more than 140 basins, with each agency responsible for the design and deployment of plans to achieve groundwater sustainability in a basin. Given the local nature of regulation, prices may be tailored to each basin depending on the price elasticity and the sustainability target. Before deploying price-based instruments on a statewide scale, we need to improve our understanding of what drives heterogeneity in the sensitivity of groundwater demand to prices.

Revenues from groundwater prices or auctioned permits under cap-and-trade may generate revenues to fund the development of alternative water supplies. We see this approach taking shape in regions of California, including the Pajaro Valley and Coachella Valley. These water agencies have introduced groundwater pricing to fund the artificial recharge of groundwater supplies and the development of recycled water deliveries, respectively. Given relatively inelastic demand at observed price levels, a given revenue-generating goal could be achieved with a relatively small tax.

5. CONCLUSION

Policies to improve the allocation of water resources and to encourage conservation have long been studied by economists, but climate change is renewing the importance of these issues.

Fundamental to understanding the potential impacts of water policies and the role for water trading are credible estimates of the price elasticity of demand for water. In this article, we review the water resource economics literature, with a particular focus on recent empirical estimates of the price elasticity of demand for water in the urban and agricultural sectors. We outline market failures in both surface water and groundwater and then discuss how price elasticity estimates can inform water policies to address these market failures.

A central result that emerges from our review of the recent empirical literature on water demand is the vast heterogeneity in price elasticities both within and across sectors. The range of estimates in both the urban and agricultural settings arises because of differences in data, research design, price variation, water source, environmental conditions, and regulatory settings. Demographics also influence the residential price elasticity, and the agricultural landscape affects the agricultural price elasticity. Despite this variation in estimates, most studies report that demand is relatively inelastic at observed price levels. Urban elasticity estimates since Dalhuisen et al.'s (2003) publication hover around −0.4, while agricultural estimates since those reported by Scheierling et al. (2006) average −0.5.[7]

These results have implications for water policy, including the potential gains from additional surface water transfers and the potential effectiveness of price instruments for managing groundwater. Heterogeneity in price elasticities suggests that the magnitude of gains from surface water transfers may be large. Groundwater pricing is a cost-effective tool for managing groundwater, but spatial variation in elasticity estimates suggests that the degree of conservation achieved will vary by basin.

Elasticity estimates across both urban and agricultural settings have made large strides in the last 15 years by advancing the use of quasi-experimental methods and by empirically exploring possible explanations for differences in the price sensitivities across settings. Bringing this empirical rigor to the commercial, industrial, and environmental settings will be important for advancing our broader understanding of water resource economics and policy, as will further explanation of the drivers of heterogeneity across settings.

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[7]These reflect simple averages of estimates reported in **Tables 1** and **2**, excluding those for which we report a range.

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