Transaction Costs and the Gains from Trade in Water Markets

Nick Hagerty*

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Abstract

This paper estimates the potential benefits of reducing transaction costs in California's surface water market. I develop an empirical framework to analyze welfare in a water market that uses transactions data, inferring the preferences of water districts from their prior behavior. I separate observed prices into demand and transaction costs and then simulate a market without transaction costs. Gains from efficient trading are \$224 to \$614 million per year, with larger gains in dry years. Physical conveyance costs prevent further gains, making some price dispersion inevitable. Contracting and regulatory reviews impose transaction costs that policy reform can alleviate.

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1 Introduction

Water supplies are becoming scarcer and more variable in many parts of the world (UNDP 2006). Fueled by population pressure and climate change, water scarcity can increase poverty and conflict (Sekhri 2014; Burke et al. 2015) and is set to worsen in the coming decades (World Bank Group 2016). To help societies adapt, many observers advocate for greater use of water markets. Like other markets, water markets may yield benefits by allocating scarce resources to the most valuable uses and allowing participants to flexibly respond to changing conditions. But formal and large-scale water markets are still rare, even in wealthy countries with strong legal institutions (Brewer et al. 2008; Olmstead 2010). Why? A rich qualitative literature points to unique institutional features of water, complex political economy issues, and transaction costs (Leonard et al. 2019). But relatively little quantitative evidence is available to assess the magnitudes of these barriers and set priorities for reform.

This paper quantifies the importance of transaction costs in California's wholesale surface water market, the largest in the United States. I ask: How large are the potential gains from eliminating transaction costs? In other words, by how much is water misallocated at present, and by how much could it be improved through policy reform? To answer this question, I develop a new empirical framework to estimate demand in the presence of transaction costs that relies on transactions data. The idea is to infer the preferences of water districts – the local government agencies that supply water to farms and households and control most water rights – from their observed behavior in the market that already exists. After separating observed prices into demand and transaction costs, I use the demand model to simulate a market without transaction costs and estimate the gains from expanded trade.

Two reasons make California's water market a useful setting in which to study the role of transaction costs. First, transaction costs are likely binding constraints. Water transfers are already technologically feasible; a comprehensive network of canals, pipelines, rivers, and reservoirs connects nearly all water users in the state. Property rights are relatively strong: the basic legal basis for using and selling water is well-defined, and regulatory processes for transferring water exist

(Leonard et al. 2019). Second, anecdotal evidence suggests the potential gains from reallocating water could be large. California has a large and diverse economy, but most of it depends on water supplies that are imported over great distances and prone to droughts. Most of this water is quantity-rationed by historical rules, and retail prices can vary over more than two orders of magnitude: in 2023, according to their websites, commercial and industrial customers in the city of San Diego paid $2,855 per acre-foot,[1] while agricultural customers in the Imperial Valley, less than a two hours' drive away, paid just $20 per acre-foot.

My starting point is to interpret the high price dispersion and low transaction volume in California's water market as equilibrium outcomes of trade with transaction costs. Transaction costs insert a wedge between observed prices and districts' marginal value of water, and they prevent other trades from happening at all. I consider a broad definition of transaction costs, akin to trade costs in the international trade literature, that includes costs from incomplete information, transportation, and regulatory approval processes. Most types of transaction costs cannot be measured directly, so instead I infer them indirectly.

I begin with a model of water districts that trade endowments of a homogeneous good with no production. Districts pay a fixed cost to enter the market and complete any transactions in a year, and they pay *ad valorem* variable costs to either sell or purchase water. Variable costs are specific to the buyer-seller pair, directionally asymmetric, and arise from both observable and unobservable determinants. Spatial arbitrage equalizes prices up to variable transaction costs. Using these assumptions, I derive an empirical model of water market prices that attributes price variation across counterparties to transaction costs and price variation over time to demand.

I estimate the model's parameters in four steps. First, I estimate variable transaction costs that arise from observable determinants, such as conveyance distance and regulatory reviews, by comparing prices across transactions made by the same district in the same year. Second, I estimate the extensive-margin decision of market entry as a function of observable factors exogenous to the market equilibrium. Third, I estimate the inverse price elasticity of demand, which measures

[1] An acre-foot, the standard unit of volume for water in the American West, is the amount of water that would cover one acre of land with twelve inches of water.

how districts' marginal value of water responds to changes in quantity consumed, using variation in annual surface water endowments generated by allocation rules in the federal and state water projects. Fourth, I estimate unobserved variable transaction costs and district-specific demand intercepts using random effects. From these estimates, I recover transaction costs and demand.

To estimate the model, I construct a comprehensive new dataset on California's water economy. For water transactions, I use a proprietary dataset that to my knowledge is the most complete in existence; crucially, it provides a nearly complete record of prices. I link the transactions data to the universe of wholesale yearly surface water deliveries in California, a new dataset assembled jointly for this paper and for Hagerty (2022). I also build a large crosswalk file to link users across datasets and years, a geospatial dataset on user locations and boundaries, and a basic hydrological model of California's water infrastructure.

In intermediate results, I find large variable transaction costs associated with specific determinants. For example, buyers receive a 45 percent discount for transactions that are subject to additional regulatory review because they originate from within a federal or state water project. Fixed costs are also important barriers to trade: Districts are less likely to trade in wetter years, when they have more recent market experience, and if they face fewer regulatory reviews across all potential transactions. I find an inverse elasticity of -1.4, implying a price elasticity of -0.69 for districts that trade. Including both observable and unobservable determinants, median variable transaction costs are 27 percent for sellers, 21 percent for buyers, and 54 percent of the transaction price in total. Marginal valuations remain highly dispersed, suggesting that gains are available from reducing transaction costs and increasing trade.

For my main result, I combine the demand model with the hydrological model to simulate an efficient market without transaction costs and calculate the resulting gains from trade. The objective is to equalize marginal valuations across districts up to purely physical transportation costs that can never be eliminated. I estimate that an efficient market would achieve gains of $224 to $614 million per year, with a present value around $12 billion. Gains are disproportionately large in dry years, suggesting that markets are especially valuable for risk management.

The gains from trade are small relative to water supply expenditures or GDP in California. I discuss several explanations. First, water is costly to move, so much of the dispersion in prices is inevitable. Second, water demand is inelastic, so dispersion can be eliminated with relatively little reallocation. Third, water districts may be trading more conservatively than their own constituents or customers would prefer. Fourth, my analysis focuses on trade between water districts, but there may be greater potential gains from water reallocation among farmers and households within districts.

However, the gains are still considerable in absolute terms and may be worth policy reform efforts. Barriers to trade arise from both traditional transaction costs (i.e., search, negotiation, contracting) and regulatory reviews, showing up in both fixed and variable costs. These types of transaction costs may be reduced by increasing market information, improving coordination, and streamlining regulatory approval processes.

This paper makes several contributions. For one, it provides a method to estimate demand in water markets that uses transactions data from the existing market. Most prior analyses of the gains from water markets couple detailed engineering models of water infrastructure with models of water demand; examples include California (Howitt et al. 1999; Sunding et al. 2002; Jenkins et al. 2003; Medellín-Azuara et al. 2007), Australia (Peterson et al. 2005; Qureshi et al. 2009), and Chile (Rosegrant et al. 2000). The demand models in these studies are typically mathematical programming models of agricultural production that rely on a large number of calibrated parameters (Mérel and Howitt 2014). A recent variation is Rafey (2023), who uses modern production function estimation techniques to value the *ex post* gains from water trading in Australia. My approach is different because it models demand of the relevant actors: water districts, not individual farmers. It is more parsimonious than the programming models and arguably more realistic because it is estimated using observed water market transactions. Even where fine-scale agricultural data is available, working directly with the revealed preferences of water districts makes my approach more policy-relevant so long as districts continue to be the primary market participants.

My approach builds on a vast literature in international trade on measuring trade costs, particularly methods that infer costs from price gaps rather than trade flows (Eaton and Kortum 2002; Donaldson 2012; Atkin and Donaldson 2015). I share the goal of indirectly estimating frictions that are difficult or impossible to measure directly, but I adapt the setup because water is homogeneous, has no production, and transaction costs are bilaterally asymmetric. My approach also can be used more generally to analyze trade of a factor endowment in the presence of transaction costs. It may be particularly relevant to environmental permit markets, complementing theoretical work by Stavins (1995) and Liski (2001), or some types of electricity markets.

I also empirically measure transaction costs in a specific market, which is uncommon outside of international trade. A handful of papers do so in financial markets (Kyle and Obizhaeva 2016), agricultural labor markets (Foster and Rosenzweig 2022), supplier contracting (Boehm 2022; MacKay 2022), and electricity markets (Jha and Wolak 2023). A few other papers evaluate the consequences of reducing transaction costs in financial services (Jack and Suri 2014; de Mel et al. 2022; Batista and Vicente 2023), the upgrade of durable goods (Hodgson 2023), and pollution permit markets (Gangadharan 2000; Cason and Gangadharan 2003). In water markets, Womble and Hanemann (2020) estimate explicit transaction costs from surveys, while Carey et al. (2002) and Regnacq et al. (2016) study the effects of transaction costs on trading quantities but not welfare. Ayres et al. (2017) study transaction costs in the governance of groundwater resources.

Finally, my results shed light on the factors constraining water markets: I show that transaction costs matter, quantify their consequences, and provide evidence on which types are most important. Empirical evidence on water markets has long been limited by both data and methods; I make progress on both. This paper also contributes to a broader literature on the costs of misallocation in markets such as housing (Glaeser and Luttmer 2003), capital (Hsieh and Klenow 2009), energy (Davis and Kilian 2011), labor (Bryan and Morten 2015; Adamopoulos et al. 2017), and land (Restuccia and Santaeulalia-Llopis 2017).

2 Background

2.1 California's water market

California's water market refers to voluntary sales or purchases of the right to use surface water within the state. California's Water Code allows trading so long as the seller holds legal right to the water sold and the water would have verifiably been used otherwise (DWR and USBR 2015). Transactions are negotiated bilaterally between sellers and buyers; there is no central clearing-house. They can be temporary or permanent; my analysis focuses on within-year leases, the most common type of transaction. Most potential transactions must obtain legal approval from one or more regulatory agencies.

Most transactions are conducted by local government agencies that supply water to farms and households and hold most of the state's water rights. These agencies are often referred to as water districts. Typical sellers are water districts that serve farmers, especially those with more secure water rights and in water-rich areas. Typical buyers are water districts in urban areas, those that serve farmers in water-scarce areas and with higher-value crops, and environmental programs that seek to increase instream flows. Transactions allow districts to respond both to shocks to water supplies in dry years and to long-term shifts in water demand and urban growth (Hanak and Stryjewski 2012; DWR and State Water Board 2015).

Moving water is physically feasible, thanks to one of the world's most sophisticated systems of water infrastructure. Canals, pipelines, and rivers together connect nearly all water districts in California.[2] Canals often have spare capacity, especially when considering the ability to store water in reservoirs along the way. Their owners are required to grant access for transfers so long as there are no negative consequences (Water Code Section 1810). Legal and infrastructure barriers preclude trade with other states or countries. Groundwater is regulated separately from surface water and cannot be traded over long distances, so it falls outside the scope of my analysis.

[2]Transactions on the same river or canal are simple: the seller takes less water at one point and the buyer takes more at another. Other transactions are more complex. For example, a seller may allow more water to flow downstream to a canal intake point, where more water is pumped into the canal before traveling hundreds of miles to the buyer.

2.2 Water districts

Most water rights are held by public agencies known as special districts. Types of special districts include water districts as well as irrigation districts, flood control and water conservation districts, and municipal utility districts. A smaller share of water rights is held by cities, county water agencies, nonprofit mutual water companies, and for-profit utility companies. Individual farmers hold a large number of water rights by count but a small fraction by volume; most farmers obtain irrigation water from a district. To simplify exposition, I refer to all potential buyers and sellers as water districts, but my analysis still includes these other types of entities.

Water districts hold water rights on behalf of the farmers, households, and firms to whom they deliver water. Districts also conduct any transactions; individual farmers or households within a district are typically unable to trade directly with actors outside of the district (Chong and Sunding 2006). As a result, I focus on trade among water districts, not the gains from reallocation among farms or households within districts.[3]

Districts with different governance structures or different types of water rights may face differing incentives in the water market. For example, boards are elected by popular vote in some districts and by property-weighted vote in others. Districts that are more responsive to landowners may be more willing to sell water, because water sales often benefit landowners and harm other community members (Hanak and Stryjewski 2012; Edwards and Libecap 2015; Bruno et al. 2022). I leave aside the question of how districts reach decisions; I instead infer their preferences from their past behavior in the water market.

2.3 Water rights and allocation percentages

Many districts directly hold surface water rights, which come in two types: appropriative and riparian. Other districts hold long-term contracts to receive surface water from the federal and state water projects – California's State Water Project (SWP) and the federal Central Valley Project

[3] I also do not consider local water trading: transactions between farmers or households within a district. This is known to occur in some irrigation districts, but data is scarce.

(CVP) and Lower Colorado River operations – with the project itself holding the underlying water right.

Surface water is scarce and rationed annually, creating year-to-year variation in districts' water endowments based on precipitation and runoff in the mountains during the previous winter. I use this variation to estimate the price elasticity of demand. Most variation comes from the SWP and CVP. Deliveries from these projects are based on a time-invariant maximum volume (specified in each district's contract) multiplied by each year's allocation percentage. Allocation percentages are determined separately for each of 13 categories of contracts, grouped by history, geography, and sector. Some categories tend to have priority over others, but the ordering is not constant, due to regional differences in water conditions (Stene 1995). Allocation percentages do not fully determine water deliveries and consumption for several reasons: besides water market transactions, a water district can choose to take less than its allocation, bank water for temporary storage, or apply to receive extra water under certain circumstances.

Other sources of surface water are more stable over time. The Lower Colorado system never experienced a shortage prior to 2023. Appropriative water rights follow a seniority rule determined by the date of first use; in dry years, senior rights-holders are entitled to their full claim before junior rights-holders are entitled to any. In practice, most large water rights are senior to the projects themselves, so the largest cutbacks fall upon project contractors.

2.4 Transaction costs

My view of transaction costs follows Leonard et al. (2019), who define them broadly as "the costs of defining, exchanging, and enforcing water rights." My analysis includes the traditional definition of transaction costs, which focuses on information, search, negotiation, and enforcement (Coase 1937; Demsetz 1968; Williamson 1979; Barzel 1982). It also includes other costs identified in the water markets literature that arise from the need to obtain regulatory approval and to physically transport the water. A brief typology follows; more details can be found in Colby (1990); Archibald and Renwick (1998); McCann and Easter (2004); and Regnacq et al. (2016).

Administratively-induced costs. Following Archibald and Renwick (1998), these are search, negotiation, and contracting costs that are not unique to water markets. First, a potential buyer or seller must identify opportunities for trades, find a willing trading partner, and learn about their preferences. This happens mostly by word of mouth in social networks; sometimes a professional broker helps with matchmaking. Second, the districts must negotiate over the sale price and quantity as well as the duration, payment terms, delivery date, point of delivery, and delivery pathway. Third, they must draft a contract and later enforce it. These steps may generate considerable costs, both explicit (e.g., attorney fees, broker fees) and implicit (e.g., time and hassle costs), borne by both buyers and sellers. Negotiation costs may also exist within each district, among the board members and other internal stakeholders that must agree upon a course of action and overcome hold-up problems. Administratively-induced costs cannot be fully eliminated, but they can be reduced by providing more market information and institutional reform to improve coordination, resolve conflicts, and enforce contracts (Libecap 2005).

Delivery costs. These are the costs that relate to physically moving the water from seller to buyer. First, there are several explicit costs of transporting water. A fraction of water is lost in transit to evaporation and percolation, and energy is required to pump water into canals and over mountain ranges. Infrastructure owners assess "wheeling charges" that typically exceed the marginal cost of conveyance in order to cover operations, maintenance, and sometimes capital costs. Transfers that cross the Sacramento–San Joaquin Delta incur "carriage losses," in which between 20 and 35 percent of the water is sent to sea to maintain the direction of flow and protect water quality for both ecosystems and other water rights (DWR and USBR 2015).

Second, infrastructure constraints impose implicit costs in the form of risk over delivery success. Most constraints, like maximum canal capacities, are rarely binding for proposed transfers (Hanak and Stryjewski 2012). The main exception is for transactions that cross the Delta, where difficult-to-predict pumping restrictions are required by federal law to protect certain species of fish. Because the projects are sometimes not allowed to pump water into their canals, there is no guarantee that the seller's water will reach the buyer (DWR and USBR 2015).

The Delta constraint could be remedied through the construction of new infrastructure or reform to the Endangered Species Act, though either would bring new costs that would need to be weighed against the benefits. Purely physical conveyance costs – energy, conveyance losses, and carriage losses – cannot be remedied, so I model them separately and include them in simulations.

Policy-induced costs. Following Colby (1990), these are the costs of obtaining legal approvals for a water transfer and complying with the ongoing terms of the approval. Depending on the origin and destination, proposed transactions may require review and approval by the State Water Resources Control Board (SWRCB), Department of Water Resources (DWR), and/or the U.S. Bureau of Reclamation (USBR), and environmental impact analysis under the National Environmental Policy Act (NEPA) and the California Environmental Quality Act (CEQA) (California State Water Board 1999; DWR and USBR 2015).

These reviews are intended to prevent negative externalities. A central objective is to determine the fraction of a water right that is consumptive use and therefore can be withdrawn from the system without harming downstream users, a scientifically challenging task. Reviews also evaluate other impacts to ecosystems, instream flows, groundwater, and to local economy in the area of origin (Chong and Sunding 2006). Because they function to measure and verify the asset, these reviews can be viewed as crucial institutions to clarify and protect property rights (Libecap 2005). But the costs they impose on districts may be greater than necessary, and environmental reviews have been found to impose large costs in other sectors (Brooks and Liscow 2023; Bennon et al. 2024). By introducing asymmetric scrutiny for transferring water relative to using it in the first place, and by seeking to avoid any external costs rather than conduct benefit-cost analysis, these reviews seem likely to produce inefficiently few transfers.[4]

To apply for approvals, districts must pay fees to attorneys and engineers for document prepara-

[4] One water district complained that "literally anyone can posit a potential environmental or third-party impact… and either block the transfer or make it too expensive to complete" and claimed that "the she[e]r complexity of the current water transfer process… is enough to stop most potential transfers from even being proposed" (Western Water Company 2000).

tion and to the reviewing agencies as compensation for staff time (Scheer 2016). After the transfer, the seller also must implement a monitoring and mitigation plan for third-party effects (DWR and State Water Board (2015)). Districts also may incur implicit costs of hassles, delays, and uncertainty of approval, as well as the risk of litigation afterward (Colby 1990). Policy-induced transaction costs could be remedied through reform to simplify and standardize the approval processes, including up-front investment in hydrological modeling, to reduce the marginal resources required to evaluate each new transaction (Culp et al. 2014; Gray et al. 2015; Association of California Water Agencies 2016).

Some of these transaction costs are likely incurred by a district for participating in the market at all. Others are specific to the pair of districts who trade, as they depend on the delivery pathway and required regulatory reviews. All types of transaction costs may be incurred by both buyer and seller. For example, although sellers pay the regulatory approval fees, Scheer (2016) reports that they typically invoice buyers for reimbursement. Details of contract provisions are scarce, so rather than assuming how transaction costs are shared between buyers and sellers, I estimate their nominal incidence from the data.

3 Model

I model trade of surface water among water districts in the presence of transaction costs.

3.1 Assumptions

Each district j begins each year t with an endowment of water E_{jt}. There is no production, and water is a homogeneous good.[5] Districts make bilateral transactions indexed by i.

Assumption 1 (Demand)**.** *Each district has an inverse demand function $V_{jt}(Q_{jt})$, which gives marginal valuation V_{jt} as a function of quantity consumed Q_{jt}. Demand is isoelastic, varies across*

[5] Because a buyer receives all water through the same infrastructure, water quality does not vary across potential sellers. It is not literally the same molecules of water that are being sold but rather a series of changes in flows. Few contracts specify water quality (McCann and Easter 2004).

districts, and may shift over time:

$$\ln V_{jt} = \eta_j \widetilde{\ln Q}_{jt} + \bar{v}_j + v_{jt} \tag{1}$$

where $\mathbb{E}[v_{jt}] = 0$*, and log quantity consumed is centered on the district mean.*[6]

Note this is demand for surface water consumption, not for market transactions. Demand describes not how trade itself responds to price, but rather how marginal valuations of water respond to surface water quantity.

The most substantive restriction is that a district's marginal valuation V_{jt} is constant across transactions i within the year t. This restriction follows from the plausible assumption that each year's transactions are planned simultaneously, and it is crucial for separating demand from transaction costs. The isoelastic functional form is important in estimation for its analytical tractability, but it is not crucial for extrapolation, and in simulations I explore alternative functional forms. I also implicitly assume that water districts have well-defined preferences, but I make no assumptions about how these preferences form.

Assumption 2 (Transaction costs)**.** *District j pays a fixed cost f_{jt} to enter the market and complete any transactions. Then, both sales and purchases incur variable transaction costs that are* ad valorem *(iceberg): District j must give up τ^s_{jk} units of water to sell 1 unit to another district k, and τ^b_{jk} units to buy 1 unit from district k, where $\tau^s_{jk}, \tau^b_{jk} \geq 1$ for all j, k.*

Fixed costs vary across districts and years but are restricted to be constant across counterparties. Fixed costs likely capture many kinds of both administrative-induced and policy-induced transaction costs, and it is plausible that they are associated with market entry rather than with specific counterparties. This restriction is necessary for theoretical and empirical tractability; inferring fixed trade costs from prices is a challenge in the international trade literature as well (Atkin and Donaldson 2015).

[6] $\widetilde{\ln Q}_{jt} \equiv \ln Q_{jt} - \overline{\ln Q}_j$, so that the intercept $\bar{v}_j$ represents mean log marginal valuation.

Variable costs vary across buyer-seller pairs and are bilaterally asymmetric. They likely capture many kinds of delivery costs and policy-induced costs, as well as some forms of administrative-induced costs. Many transaction costs are reasonable to think of as scaling with volume; conveyance and carriage losses are a constant fraction of water transferred, and larger transactions attract more regulatory scrutiny. The iceberg specification is uniquely tractable and consistent with the international trade literature (Anderson and van Wincoop 2004). Unlike the international trade literature, I distinguish between costs paid by the seller and the buyer. Variable costs are constant over time, a key restriction that allows me to separate transaction costs from demand.

Assumption 3 (Determinants of transaction costs)**.** *Variable transaction costs result from observable and unobservable determinants that are multiplicatively separable:* $\ln \tau^s_{jk} = \rho^s \mathbf{B}_{jk} + \check{\tau}^s_{jk}$ *(for sales) and* $\ln \tau^b_{jk} = \rho^b \mathbf{B}_{jk} + \check{\tau}^b_{jk}$ *(for purchases), where* $\mathbf{B}_{jk}$ *is a vector of observable determinants, and unobservable determinants load onto* $\check{\tau}^s_{jk}$ *and* $\check{\tau}^b_{jk}$*.*

Since variable transaction costs τ^s_{jk} and τ^b_{jk} are greater than 1, they can be rewritten with a mean-zero error term using a change of variables. For each side of the market $m \in \{s, b\}$:

$$\ln \tau^m_{jk} = \rho^m \mathbf{B}_{jk} + \bar{\tau}^m_j + \tilde{\tau}^m_{jk} \tag{2}$$

where $\bar{\tau}^m \equiv \mathbb{E}[\check{\tau}^m_{jk}]$ and $\tilde{\tau}^m_{jk} \equiv \check{\tau}^m_{jk} - \bar{\tau}^m$, such that $\mathbb{E}[\tilde{\tau}^m_{jk}] = 0$. The most substantive restriction here is that cost determinants do not interact – when a transaction is subject to multiple cost determinants, total costs equal the product of their parts.

Assumption 4 (No arbitrage)**.** *If a pair of districts trades, prices equalize marginal valuations up to variable transaction costs. For an observed transaction i in year t between any two districts, where the seller is j and the buyer k:*

$$\tau^s_{jk} V_{jt} = p_{ijkt} = \frac{1}{\tau^b_{kj}} V_{kt}. \tag{3}$$

Relative to marginal valuations, the negotiated price gives a premium to the seller, and a discount to the buyer, that is exactly large enough to compensate for the variable transaction costs that each incurs. In equilibrium, each pair of districts that trade equalize their marginal valuations up to variable transaction costs, and each district equalizes its marginal valuation across all districts it trades with. Fixed costs affect who participates in the market but are then sunk, so they do not affect equilibrium prices conditional on the set of participants.

No arbitrage is the crucial assumption underpinning most of the literature on transaction and trade costs. It can be motivated in at least two ways. The first appeals to competition across districts: If a district k buys water at one price from seller j, but the price is higher than what another seller j' can offer, it will be profitable for j' to undercut the price (Anderson and van Wincoop 2004). The second motivation, which dates back to Foley (1970), relies on intermediaries who buy goods from some consumers and sell them to others, use resources, and operate in perfect competition. In a water market the intermediaries might be thought of as brokers. Appendix B.2 provides a derivation of Equation 3 using this second motivation.

The main reason that Assumption 4 might not hold is if there is market power on either side of the market. I investigate this possibility in an appendix to an earlier working paper (Hagerty 2019) and find little evidence of market power by either buyers or sellers. A separate and contemporaneous analysis by Tomori et al. (2022) finds similar results in the same setting.

Not all pairs of districts trade with each other. Trade will not occur if variable transaction costs are greater than the gap in marginal valuations, or if fixed transaction costs are too large. But since the good is homogeneous, the absence of trade does not imply that transaction costs were too large. Each district might achieve Equation 3 by trading with a different partner instead, resulting in the sparse trading network seen in the data.

Not all districts trade at all. District j enters the market only if the potential surplus from trading makes up for the fixed cost of entry:

$$f_{jt} \leq S_{jt}(q_{jt}, Q_{jt}) \tag{4}$$

where q_{jt} is the potential trading quantity (i.e., net volume purchased in the market if entered), Q_{jt} is total quantity consumed, and potential surplus S_{jt} is the integral of inverse demand over the trading quantity less the sum of prices paid and transaction costs incurred.

3.2 Identification

To take the model to data, I take logs of Equation 3 and allow for a mean-zero residual term, $\mathbb{E}[\epsilon_{ijkt}] = 0$, which might represent errors in measurement or in districts' optimization.[7] For sellers and buyers:

$$\begin{aligned} (Sellers) \qquad \ln p_{ijkt} &= \ln V_{jt} + \ln \tau^s_{jk} + \epsilon_{ijkt} \\ (Buyers) \qquad \ln p_{ijkt} &= \ln V_{jt} - \ln \tau^b_{jk} + \epsilon_{ijkt}. \end{aligned} \tag{5}$$

For a given district, these equations attribute price variation across counterparties to differences in transaction costs, and price variation across years to changes in marginal valuations. Combining equations for buyers and sellers and substituting equations 1 and 2 yields a full model of water market prices:

$$\ln p_{ijkt} = \rho \mathbf{B}_{jk} + \eta_j \widetilde{\ln Q}_{jt} + \bar{v}_j + \bar{\tau}_j + \tilde{\tau}_{jk} + v_{jt} + \epsilon_{ijkt} \tag{6}$$

where $\rho \equiv (1-b)\rho^s - b\rho^b$, $\bar{\tau}_j \equiv (1-b)\bar{\tau}^s_j - b\bar{\tau}^b_j$, $\tilde{\tau}_{jk} \equiv (1-b)\tilde{\tau}^s_{jk} - b\tilde{\tau}^b_{jk}$, and b is an indicator that takes a value of 1 for buyers and 0 for sellers.

In Equation 6, the demand intercept $\bar{v}_j$ and the mean level of unobserved transaction costs $\bar{\tau}_j$ are not separately identified in transactions data without further restrictions. To identify them, I use a technique inspired by stochastic frontier analysis (Aigner et al. 1977; Kumbhakar et al. 2022).[8]

Assumption 5 (Unobserved transaction costs)**.** *For each district, trade with at least one counter-*

[7] The alternative would be to allow time-varying transaction costs to absorb the residual price variation, as in Hagerty (2019). Here, the additional structure from time-constant transaction costs helps me identify the unobserved transaction costs $\tilde{\tau}^b_{jk}$.

[8] Stochastic frontier analysis was developed to estimate one-sided deviations from an unobserved frontier. Its usual application is firm inefficiency relative to a production frontier, but the basic setup also describes transaction costs relative to marginal valuations.

party carries no variable transaction costs: $\min_k\{\tau^s_{jk}\} = 1$ *and* $\min_k\{\tau^b_{jk}\} = 1$ *in the observed data for each district* j.

This assumption shifts the distribution of unobserved transaction costs, setting their means to a level that guarantees that overall transaction costs are never a negative percentage of the transaction ($\tau_{jk} \geq 1$), enforcing Assumption 2. For each side of the market $m \in \{s, b\}$, I can recover

$$\bar{\tau}^m_j = -\min_k \left\{\rho^m \mathbf{B}_{jk} + \tilde{\tau}^m_{jk}\right\}. \tag{7}$$

The demand intercept $\bar{v}_j$ is then shifted (down for sellers, up for buyers) by the amount of these unobserved transaction costs. The mean shifter $\bar{\tau}^m_j$ creates distance between marginal valuations and equilibrium prices for unobserved determinants the same way that the term $\rho^m \mathbf{B}_{jk}$ does for observed determinants. It allows me to capture transaction costs that are uncorrelated with the observed determinants. The alternative to Assumption 5 would be to assume that unobserved transaction costs are mean-zero distributed around the observed determinants, as in much of the international trade literature (e.g., Helpman et al. 2008), but in water markets such an assumption would likely miss important unobserved costs.

Unobserved variable transaction costs are identified only relative to the least costly transaction.[9] If there are large unobserved variable transaction costs that districts incur across all transactions, I will underestimate the dispersion in marginal valuations and the potential gains from trade.

4 Estimation

The econometric model I take to data is a version of Equation 6 that combines a few terms. For transaction i made by district j with counterparty k in year t, log price p_{ijkt} is explained by observable determinants of transaction costs $\mathbf{B}_{jk}$, log quantity consumed $\widetilde{\ln Q_{jt}}$, a district-specific

[9]This is also a limitation of stochastic frontier analysis, in which efficiency is identified only relative to the most efficient firm.

intercept $\delta_j \equiv \bar{v}_j + \bar{\tau}_j$, district-pair-specific transaction costs $\tilde{\tau}_{jk}$, and an error term $\varepsilon_{ijkt} \equiv v_{jt} + \epsilon_{ijkt}$:

$$\ln p_{ijkt} = \rho \mathbf{B}_{jk} + \eta_j \widetilde{\ln Q_{jt}} + \delta_j + \tilde{\tau}_{jk} + \varepsilon_{ijkt}. \tag{8}$$

To estimate Equation 8, I propose a four-step procedure that involves sequentially estimating parameters and moving their terms to the left-hand side. This multi-stage procedure allows me to isolate different sources of identifying variation best tailored to estimate each parameter.[10] After estimation, I use Equation 7 to separate δ_j into $\bar{\tau}_j$ and $\bar{v}_j$, giving me all the terms I need to recover transaction costs (Equation 2) and demand (Equation 1).

4.1 Step 1: Variable Transaction Costs from Observable Determinants

I estimate observable variable transaction costs ρ incurred by both sellers and buyers by regressing observed prices on a vector of transaction cost determinants $\mathbf{B}_{jk}$:

$$\ln p_{ijkt} = \rho \mathbf{B}_{jk} + \alpha_{jt} + \epsilon^1_{ijkt}. \tag{9}$$

District-by-year fixed effects α_{jt} absorb the other terms from Equation 8. They ensure that coefficients ρ measure price gaps across transactions within district and year. For example, suppose a seller completes transactions with two different buyers in the same year, of which one requires the seller to undergo a particular regulatory review and the other does not. The seller is indifferent between buyers at the margin, so the price gap reveals the equilibrium price premium that compensates the seller for the regulatory review. If the review is also costly to the buyer, then this transaction will offer the buyer an equilibrium price discount relative to the buyer's other sellers.

Because the sample of transactions is not large, I avoid overfitting the model by using the least absolute shrinkage and selection operator (lasso) to perform variable selection (Belloni et al. 2014). Many cost determinants are *a priori* plausible, yet not all may be empirically important; others will

[10] In principle Equation 8 could be estimated all at once, but it would require stronger econometric assumptions that are inconsistent with theory and the institutional context.

be set to zero. I cluster standard errors by district to account for correlation over time, and also by transaction to adjust for the fact that each transaction appears multiple times in the dataset, once for each party. In some specifications, I use coarser fixed effects to explore robustness.

4.2 Step 2: Market Entry

I estimate the extensive-margin decision of whether to enter the water market in a given year using a probit model. I regress a binary indicator for whether district j completes any transactions in year t on a set of district-level explanatory variables $\mathbf{Z}_{jt}$, some of which are time-varying:

$$\text{Enter}_{jt} = 1\left(\Pi\mathbf{Z}_{jt} + \epsilon^2_{jt} > 0\right). \tag{10}$$

I cannot estimate fixed costs directly, since they are identified only by potential surplus (Equation 4), which is unobserved when market entry does not occur.[11] But the extensive margin is sufficient to model the *consequences* of fixed costs. I simulate a market with fixed costs by modeling trade among districts predicted to enter the market, and I simulate a market without fixed costs by setting the probability of market entry to 1 for all districts.

Explanatory variables are observable factors that are exogenous to the market equilibrium: determinants of annual endowments, prior experience with the market, and time-invariant district characteristics.[12] Endowment determinants are allocation percentages, using the full set of instrumental variables described in Step 3. Prior experience variables are lags of the dependent variable. I use the lasso to select explanatory variables from the full set, and I cluster standard errors by district.

[11] Potential surplus depends on potential quantities traded q_{jt} and consumed Q_{jt}, which are endogenous, and it is beyond the scope of this paper to model the entire network of bilateral trading quantities. A second-order approximation to the demand curve can express potential surplus as proportional to q^2_{jt}, but I do not have an analytical expression for q_{jt}, nor is it a monotonic function of endowments or other market primitives, so I cannot use a Tobit or other censored data model to recover potential surplus.

[12] District characteristics are: an indicator for serving primarily municipal (versus agricultural) consumers, indicators for holding rights or contracts under each major water source (CVP, SWP, Colorado River, and appropriative or riparian rights), latitude, and log maximum water rights (including project contracts).

4.3 Step 3: Demand Elasticity

I estimate the inverse price elasticity of demand η using instrumental variables. Recall that this elasticity measures the sensitivity of districts' marginal valuations to changes in quantity consumed (not quantity traded). First, I adjust observed prices for the variable transaction costs estimated in Step 1. Then, I regress adjusted log prices on log quantity consumed:

$$\ln p_{ijkt} - \hat{\rho}\mathbf{B}_{jk} = \eta \widetilde{\ln Q_{jt}} + \alpha_j + \hat{\lambda}_{jt} + \theta t + \epsilon^3_{ijkt}. \tag{11}$$

District fixed effects α_j ensure that the elasticity is identified from within-district variation over time. In principle, the elasticity may be heterogeneous across districts; in practice, for precision and to avoid weak instrument problems, I estimate a single average elasticity for the market.

Instruments. To overcome the joint determination of prices and quantities, I instrument for quantities using exogenous changes in annual endowments: allocation percentages in the federal and state water projects. Allocation percentages are determined by precipitation in the mountains during the previous winter, making their year-to-year variation exogenous to demand.[13] They are relevant instruments because transaction costs create inertia in endowments. Figure A1 plots allocation percentages aggregated to several regional categories.

My instruments are log allocation percentages for the district itself, all other districts in the same hydrologic region, and all other districts in the state, and the full set of interactions between each contract type's log allocation percentage and hydrologic region indicator variables. These interactions allow allocations for each contract type (which are largely divided by region and sector) to have different effects on every other region of the state. They also yield a large number of candidate instruments.[14] To avoid overfitting and weak instruments, I estimate the model via

[13] I give a more extensive discussion of the identification assumptions in Appendix B.2.

[14] There are 13 contract types and 10 hydrologic regions, plus 3 overall instruments, for a total of 133 potential instruments. The contract types are: SWP Agricultural, SWP Municipal, CVP North of Delta Agricultural, CVP North of Delta Urban, CVP North of Delta Settlement Contractors, CVP American River Urban, CVP In Delta (Contra Costa), CVP South of Delta Agricultural, CVP South of Delta Urban, CVP South of Delta Settlement Contractors, CVP Eastside Division, CVP Friant Class 1, and CVP Friant Class 2. All instruments are log-transformed to match

post-lasso two-stage least-squares, following the IV lasso algorithm of Chernozhukov et al. (2015) as implemented in Stata by Ahrens et al. (2018). IV lasso uses data-driven penalization to choose an optimal subset of instruments.

Sample selection correction. Because prices are only observed in years for which a district enters the market, the sample may be selected in ways that bias the elasticity estimate. For example, if a district only enters the market when its endowment is very low, I might only observe prices along a relatively elastic part of its demand curve, resulting in an overestimate of the average price elasticity. To correct for sample selection, I include the inverse Mills ratio $\hat{\lambda}_{jt}$ from a version of Equation 10 estimated separately for each year of data, following Wooldridge (2010), sections 19.6.2 and 19.9.2. The selection equation includes all the same variables as the first stage for Equation 11, except for the fixed effects and time trend. It also includes the prior market experience variables, which I assume affect fixed costs of entry but not demand or variable costs, so that they can be excluded from Equation 11 and serve as the primary source of identification for the selection correction.

Time effects. A time trend θt adjusts for changes in demand over time. I omit year fixed effects to avoid spillover bias. Since transaction prices in the same market in the same year are simultaneously determined, within-year comparisons give rise to mechanical spillovers that violate the stable unit treatment value assumption (SUTVA) and eliminate most of the useful variation. Appendix C.1 offers a proof of the potentially severe bias from year effects. Although I cannot control for unobserved shocks to demand, the most important time-varying factors relate to water availability, which is flexibly captured by the instruments.

Inference. To account for estimation error in both the outcome variable and the inverse Mills ratio, I calculate standard errors by bootstrapping Steps 1-3 together. I use the Bayesian bootstrap with 1000 iterations and $\exp(1)$ weights that are blocked by district to account for correlation over

the variation of the endogenous variable, log quantities.

time.

4.4 Step 4: District Intercepts and Unobserved Transaction Costs

I estimate district intercepts δ_j and pair-specific unobserved variable transaction costs $\tilde{\tau}_{jk}$ using random effects. First, I adjust observed prices for the variable transaction costs estimated in Step 1 and the demand elasticity estimated in Step 3. Then, I regress adjusted log prices on district-level characteristics (the time-invariant variables from Step 2) and indicators for both districts and district/counterparty pairs:

$$\ln p_{ijkt} - \hat{\rho}\mathbf{B}_{jk} - \hat{\eta}_j \widetilde{\ln Q_{jt}} = \Gamma\mathbf{X}_j + \mu_j + \tilde{\tau}_{jk} + \varepsilon_{ijkt}. \tag{12}$$

I estimate this three-level random-intercept model via maximum likelihood, with district-pair effects nested within districts. The model only directly estimates the variance of district effects μ_j and unobserved variable transaction costs $\tilde{\tau}_{jk}$, but it then can be used to generate best linear unbiased predictions of both. Random effects are preferred to fixed effects in this step because they are no longer nuisance parameters – I need to use their estimates in simulations – and fixed effect estimates would be excessively noisy. I recover district intercepts by summing fitted values of covariates and predictions of district effects: $\hat{\delta}_j = \hat{\Gamma}\mathbf{X}_j + \hat{\mu}_j$. I again calculate standard errors by bootstrapping Steps 1-4 together, following the process described in Step 3.

5 Data

5.1 Water transactions

No government agency maintains a centralized listing of water transactions in California. Instead, I use a proprietary dataset on water transactions between 1990 and 2015 compiled by WestWater Research, LLC. To my knowledge, this is the most complete dataset of water transactions in California, and it has been used in federal regulatory analyses. It includes many of the same transactions as other datasets previously used in research, but it has a more complete record of prices.[15]

I focus my analysis on spot-market transactions (i.e., within-year leases) as opposed to permanent transfers of rights, because their prices are much more easily interpretable. They can be linked to demand without strong assumptions over discount rates and risk premia. In addition, volumes in leases are fixed so per-unit prices are known with certainty; volumes in permanent transfers are stochastic so per-unit prices are uncertain (Hanak 2002).

The original dataset includes 6,264 transactions, but many are unrelated to the surface water market. I exclude transactions (a) of rights to pump groundwater within adjudicated basins, (b) of rights to store water in reservoirs or groundwater banks, (c) within programs that set prices administratively, and (d) longer than one year. Of the remaining transactions, price is observed for all but 28. I carry forward 705 spot-market transactions of surface water originating in appropriative or riparian rights, SWP or CVP contracts, or reservoir storage, in which the price is freely negotiated. Appendix D describes the data processing in full detail.

5.2 Water quantities and allocation percentages

For water quantity consumed, I assemble a complete accounting of wholesale surface water deliveries and diversions in California, by district, sector, and year, from 1993 through 2015.[16] Deliveries from the SWP, CVP, and Colorado River come from archives of the DWR and USBR. Diversions on the basis of appropriative and riparian rights come from diversion reports collected by the SWRCB. The data also includes maximum contract amounts.

Allocation percentages for CVP and SWP contractors come from archives of the DWR and USBR. For appropriative, riparian, and Lower Colorado rights, allocation percentages are always 100 percent. To link districts across datasets, I build a crosswalk file that accounts for variations and errors in names as well as mergers and name changes across time. This file has 28,764 entries

[15] One dataset was assembled by Gary Libecap at UC Santa Barbara (e.g., Brewer et al. 2008), but it lacks many prices and ends in 2008. Another is maintained by Ellen Hanak at the Public Policy Institute of California, but it is not publicly available, and it appears not to focus on prices (Hanak and Stryjewski 2012).

[16] Data is publicly available at github.com/hagertynw/data-surface-water and updated through at least 2021.

(input names) pointing to 14,830 targets (output names). To identify the locations, boundaries, and areas of water districts, I combine several publicly available shapefiles into a single geospatial dataset. Details of sources, cleaning, and processing of these datasets are described in Hagerty (2022).

5.3 Hydrologic network model

I construct a basic model of California's hydrological network to calculate (a) characteristics of transaction delivery pathways, and (b) purely physical conveyance costs for simulations. The model consists of a set of nodes and edges corresponding to all major water conveyance channels in California: rivers, canals, aqueducts, and pipelines. Channels come from the National Hydrography Dataset of the U.S. Geological Survey. Each node and edge is parameterized with physical transportation costs drawn from the literature: pumping costs (for the energy required to lift water), conveyance losses (to percolation and evaporation), and carriage losses required in the Sacramento–San Joaquin Delta. I run a graph-theory algorithm to obtain the least-cost delivery pathway for each unique pair of planning areas (55 geographic regions defined by the DWR). I assign districts to planning areas based on geography. As compared with more detailed engineering models such as CALVIN (e.g., Howitt et al. 1999), this model lacks comprehensive information on capacity constraints.

5.4 Observable determinants of transaction costs

To assemble cost determinants for Step 1 of the estimation, I identify variables associated with each transaction cost described in Section 2.4 that (a) can be measured, and (b) vary across a district's counterparties. This latter criterion is necessary to measure costs through within-district price comparisons; variable costs incurred across all transactions instead load onto $\bar{\tau}_j$.

For delivery costs, I calculate four physical characteristics of delivery pathways from the hydrological model: (1) elevation gain (pump lift), (2) distance conveyed in rivers, (3) distance conveyed in canals, aqueducts, and pipelines, (4) distance of virtual movement, in which water is transferred against the direction of flow, and (5) whether the transfer crosses the Sacramento–San Joaquin Delta. Elevation gain is costly because it requires energy. Rivers produce conveyance losses. Canals have fewer conveyance losses but carry wheeling charges, which I do not otherwise observe. Virtual distance has no conveyance losses but may capture other aspects of geographical distance. Transactions that cross the Delta incur carriage losses and delivery risks.

For policy-induced costs, I identify three variables: (6) whether water is imported into a federal or state water project, (7) whether water is exported from a project; and (8) whether the transaction involves a change in the place of use of a post-1914 appropriative water right. The import and export variables capture additional reviews by DWR and USBR, and the third variable captures additional review by the SWRCB.

For administrative-induced costs, observable measures are difficult to find. Aspects that vary with distance and project membership will be picked up by variables (1)-(8). I add one more variable: (9) whether the counterparty primarily uses water in agriculture. Transactions that involve agriculture may be more complex to contract and require more ongoing monitoring.

5.5 Merged dataset and summary statistics

I construct a balanced panel of surface water quantity consumed for all 2,380 districts in California that consume at least 100 acre-feet per year.[17] To this dataset I merge the list of transactions observed for each district, such that each transaction is repeated for each buyer or seller involved. I keep transactions even when they do not successfully match the water quantity data, allowing me to use all available data at each step of the estimation: Steps 1-2 use data from 1990-2015, including districts without quantity data, while steps 3-4 use data from 1993-2015 for districts with quantity data.[18] The final dataset has 1,259 transaction-by-district observations, plus 59,165

[17] As measured by maximum water rights or average quantity consumed, whichever is greater. Water rights smaller than 100 AF/year constitute 67 percent of the count of observations but only 0.2 of total water consumption; they are generally held by individual farmers and rural households not served by any water or irrigation district.

[18] Unmatched districts represent 14% of the transaction-district observations and generally fall into two categories: associations that occasionally trade on behalf of multiple districts, and small districts that hold affiliations or agreements with larger districts instead of their own water rights or contracts. I drop a small number of districts not identified with enough specificity to determine the transaction cost variables. I also drop those that purchase water for instream

records of water quantity and market nonparticipation for years in which districts do not trade and for districts that never trade.

Table 1 shows summary statistics. Panel A shows that the mean transaction price is $236 per acre-foot (in 2010 dollars) and the distribution of volumes is highly skewed. Panel B shows that most sales come from agriculture, but purchases are shared across sectors. Panel C shows that the most exports are from the Sacramento River hydrologic region and the most imports are from the South Coast and Tulare Lake regions. Figure 1, Panel (a) shows that the distribution of prices is highly dispersed even after adjusting for year.

6 Results

6.1 Step 1: Variable Transaction Costs from Observable Determinants

Table 2, reports estimates of Equation 9. Positive coefficients reflect positive transaction costs on both sides of the market – price premiums for sellers and price discounts for buyers – because regressors for buyers are multiplied by -1, following the substitutions in Equation 6.

Columns (4)-(6) show the variable transaction costs associated with factors selected by the lasso. Column (6) is my preferred specification, with seller-by-year and buyer-by-year fixed effects. Several factors are indeed costly. For example, buyers pay approximately 45 percent less for transactions that involve exporting water from a federal or state water project, and sellers accept approximately 31 percent more for transactions that must cross the Sacramento–San Joaquin Delta.[19] Other costly determinants are distance conveyed in rivers and having an agricultural buyer (for sellers), and review by the State Water Board (for buyers).

Not all coefficients are statistically distinguishable from zero, but the fact they were selected by the lasso suggests they matter for the overall model. The importance of some of these factors is also

flows and other environmental purposes, rather than for consumptive use in the agricultural and municipal sectors.

[19] The finding of transaction costs associated with the Delta is particularly reassuring given that it is consistent with the previous results of Regnacq et al. (2016), which studies trade frictions in the same setting using a model of trade flows rather than prices.

supported by the specifications with coarser fixed effects in columns (4)-(5), in which the Delta-crossing coefficient is larger and more precise. Across specifications, all lasso-selected coefficients are positive, supporting the assumptions of the model and the interpretation of these estimates as variable transaction costs.

Results without variable selection are given in columns (1)-(3). When including all proposed cost determinants, many coefficients are not statistically distinguishable from zero, and some are negative.[20] Still, the overall patterns are broadly consistent across specifications: Buyers require price discounts, and sellers require price premiums, to complete transactions that are subject to these cost determinants.

6.2 Step 2: Market Entry

Table 3, column (1) reports estimates of Equation 10. The model is highly predictive of the market entry decision: the pseudo-R^2 shows that just a handful of regressors explain 59 percent of the variation.

Results provide evidence that fixed costs are important barriers to trade. First, districts are less likely to trade when the rest of the state has greater water allocations, meaning that drier conditions induce more districts to enter the market. This is likely because in wet years, fewer districts find the potential surplus from trading large enough to overcome the fixed costs of market entry. This result also suggests that California's system of water allocation is more efficient in wet years than in dry years.

Second, larger districts – those that hold more water rights or greater maximum contract amounts – are more likely to trade, probably because they have greater potential surplus. Third, districts in the CVP and SWP are more likely to trade, likely because transactions within the projects are streamlined and exempt from SWRCB review. Fourth, districts are more likely to trade given more trading experience in recent years, suggesting that market experience reduces

[20] Negative coefficients may simply represent reduced costs relative to another determinant. For example, most transactions that involve importing into a project are also subject to State Water Board review, and the sum of those two coefficients is always positive.

fixed costs. Market experience coefficients are all statistically significant, confirming that they provide independent sources of variation for the sample selection correction.

6.3 Step 3: Demand Elasticity

The rest of Table 3 reports estimates of Equation 11. Columns (2) and (3) show first-stage and reduced-form regressions using only two overall instruments: the district's own allocation percentage, and the allocation percentage for all other districts in the state. The instruments appear relevant and strong, with an F-statistic that exceeds conventional rule-of-thumb values. Effects point in the expected direction: greater allocations increase quantity consumed and decrease adjusted prices (i.e., marginal valuations). Allocations to other districts matter more than own allocations, which makes sense for the sample of years in which districts trade; once a district sinks the fixed cost of market entry, its quantities and prices are determined in statewide equilibrium.

Column (4) shows results of the IV lasso regression, which selects 3 instruments. The estimated inverse price elasticity of demand is −1.4, implying that if quantity consumed increases by 10 percent, marginal valuations fall by 14 percent. The first-stage F-statistic is even larger than in column (2) because the instruments are now selected optimally. Table A1 shows that the estimate is robust to more flexible time trends, the set of candidate instruments, omitting the sample selection correction, and using unadjusted prices.

This is the first estimate of the price elasticity of demand for water districts in California's surface water market. The reciprocal of my estimate implies that, conditional on trading at all, districts' price elasticity of demand is −0.69. Previous studies estimate the demand of retail consumers, generally finding it to be more inelastic.[21] This comparison suggests that districts are more price-sensitive than their own retail customers, although the estimates might not be directly

[21] For municipal water demand, my elasticity is considerably larger than a previous estimate for urban water districts in California (Buck et al. 2016, −0.14) and the mean in a meta-analysis across the US (Dalhuisen et al. 2003, −0.41) though in line with an estimate for Riverside County (Baerenklau et al. 2014, −0.76). For agricultural water demand, my elasticity is considerably larger than estimates for groundwater use in California (Bruno 2017, −0.19) and Kansas (Hendricks and Peterson 2012, −0.10), as well as a meta-analysis across the US (Scheierling et al. 2006, −0.48). In these studies, even when quantity data is at the district level, the price under question is the retail price.

comparable due to differing samples.

6.4 Step 4: District Intercepts and Unobserved Transaction Costs

Table A2 reports estimates of Equation 12. Many district-level covariates are statistically significant, and district and district-pair effects explain a large share of the residual variation. I use this estimated model to predict district intercepts δ_j and unobserved variable transaction costs $\tilde{\tau}_{jk}$. I then recover the mean of unobserved transaction costs $\bar{\tau}_j$ from $\hat{\tilde{\tau}}_{jk}$ and observed transaction costs $\hat{\rho}\mathbf{B}_{jk}$ (Equation 7), the mean district marginal valuations $\bar{v}_j$ from $\hat{\delta}_j$ and $\hat{\bar{\tau}}_j$ (Equation 8), and inverse demand from $\hat{\bar{v}}_j$ and the price elasticity $\hat{\eta}$ (Equation 1). I use this demand model to calculate fitted values of marginal valuations for each district in each year. For districts never observed trading, $\bar{v}_j$ is not identified, so I extrapolate the model by regressing estimates $\hat{\bar{v}}_j$ on district covariates and generating fitted values.[22]

Figure 1 plots the resulting distributions of estimated marginal valuations and variable transaction costs in dollar terms, with raw prices for comparison. There is still considerable dispersion in marginal valuations, suggesting that gains are available from reducing transaction costs and increasing trade. Median variable transaction costs are 27 percent on the seller side and 21 percent on the buyer side, for a total of 54 percent of the transaction price.[23]

7 Simulations

Using this demand model, I simulate counterfactual water market scenarios without transaction costs and calculate the resulting gains from trade. To make the computation feasible, I simulate trade among the 154 largest water districts that consume 85 percent of the water in California.[24]

Because the gains from trade may be very different under different environmental conditions,

[22] Covariates are the same as in Table A2 plus hydrologic region indicators.

[23] Values do not sum due to log transformations.

[24] I select these districts using a cutoff in mean quantity consumed of 25,000 AF/year. Because surplus is approximately proportional to the square of trading quantity, these districts are likely responsible for more than 85 percent of the potential gains from trade.

I run simulations under three water conditions: a wet year, a median year, and a dry year. These conditions use observed quantities and trading volumes from the years 2006, 2010, and 2014, respectively.[25] Figure 2 maps these fitted marginal valuations in the median-year scenario for each planning area, averaging across districts and weighting by quantity consumed.

7.1 Surplus from the existing market

I first calculate the economic surplus achieved to date by observed transactions. Figure 3, Panel (a) maps the geographic patterns of these transactions. Sellers tend to be in the Sacramento Valley and northern San Joaquin Valley; buyers tend to be in urban coastal areas and the southern San Joaquin Valley. Table 4, Panel A, reports that the total volume of water traded ranges between 35,000 and 289,000 acre-feet per year depending on water conditions.

Surplus for each district S_j (suppressing time subscripts) is the difference in marginal valuations before and after trading, integrated over the quantity traded q_j (i.e., net purchases) and evaluated using the estimated demand model (Equation 1):

$$S(q_j, Q_j) = \int_{Q_j - q_j}^{Q_j} \Big[V_j(\varphi) - V_j(Q_j) \Big] d\varphi. \tag{13}$$

Table 4, Panel A reports that observed transactions result in economic surplus of \$8.3 million per year in a median year – a figure that is small relative to annual water-related expenditures in California.[26] In a wet year, total gains are larger but still relatively small, at \$54.8 million per year.

7.2 Counterfactual simulations

To simulate an efficient market, I solve the social planner's problem in a constrained optimization problem. Because an ideal market could implement the efficient allocation, the increase in surplus

[25] Summing water quantities across the state, 2006 is the wettest year in my data, 2014 the least, and 2010 is the median year over the 1998-2015 period.

[26] Hanak et al. (2014) estimate that federal, state, and local agencies spent \$16.9 billion on water supply, and \$30.5 billion on all water-related spending (including pollution control, flood management, ecosystem management, and debt service) per year between 2008 and 2011.

represents the potential gains from trade. Because even an ideal market cannot avoid the physical costs of water conveyance, I include pair- and direction-specific conveyance costs from my hydrological network model as costs in the objective function.[27]

The social planner chooses the vector of bilateral transaction quantities q_{jk} (net volumes delivered from district j to district k, for all unique pairs $k > j$) that maximizes the aggregate value of water net of physical transaction costs, subject to the resource constraint. Aggregate value is the area under each district's demand curve between observed quantities Q_j and the simulated final quantity Q_j^f, summed over districts. Conveyance costs are per-unit and directionally asymmetric. The resource constraint requires that final quantities be nonnegative. Together, the full optimization problem is:

$$\max_{\{q_{jk}\}_{j,k>j}} \sum_j \int_{Q_j}^{Q_j^f} V_j(\varphi)d\varphi - \sum_j \sum_{k>j} \left[1(q_{jk} > 0)c_{jk} - 1(q_{jk} < 0)c_{kj}\right] q_{jk} \tag{14}$$

subject to

$$\begin{aligned} &\text{(definition of final quantities)} \quad && Q_j^f = Q_j - \sum_{k>j} q_{jk} + \sum_{k<j} q_{kj} \ \forall j \\ &\text{(resource constraint)} \quad && Q_j^f \geq 0 \ \forall j. \end{aligned}$$

I solve this problem using the `patternsearch` solver in Matlab, using observed quantities as the initial conditions. Appendix C.2 proves that the solution to this planner's problem also satisfies the conditions of an efficient market. Total gains from trade are the benefits from new transactions, calculated for each district in the same way as Equation 13,[28] plus reduced costs for the transactions already observed.[29]

[27] Appendix Figure A2 illustrates these costs.

[28] Evaluated between Q_j and Q_j^f. Appendix C.3 proves that the sum of district-specific gains across districts is equal to the objective function in Equation 14.

[29] These gains are $R_j \equiv \left(V_j(Q_j) - V_j(Q_j^f)\right) q_j$. I restrict R_j to be non-negative, since negative values occasionally arise if the simulation predicts net trading in the opposite direction of observed trading.

7.3 Gains from an efficient market

Table 4, Panel B reports simulation results. Quantities and gains are reported relative to observed trade. Scenario 2 represents my main scenario: an efficient market that accounts for physical costs of conveyance but eliminates other sources of transaction costs.

Surface water trade increases dramatically, by about 4 million acre-feet per year. Figure 3 maps geographic patterns of trade. In a median year (Panel (c)), considerable amounts of water are sold by the Sacramento Valley, northern San Joaquin Valley, and agricultural regions of Southern California, and purchased by urban coastal areas and the southern San Joaquin Valley. These patterns intensify in a dry year (Panel (d)). The most purchases are by the Los Angeles area, which is consistent with previous findings of costly water shortages in urban Southern California (Buck et al. 2016).

Total gains range from \$224 million in a wet year to \$614 million in a dry year. Eliminating transaction costs results in lower costs for transactions that already take place, but the vast majority of the gains arise from new transactions that would not otherwise occur. Results suggest that water markets are more valuable for temporarily reallocating surface water in dry years – when water is the scarcest, most valuable, and least efficiently allocated – than for permanently redistributing water across regions.

7.4 Extensions and sensitivity checks

With fixed transaction costs. To distinguish the contributions of variable and fixed transaction costs, Scenario 3 simulates a market that keeps the fixed costs of market entry but continues to eliminate variable costs other than those of physical conveyance. To keep fixed costs, I restrict trade to districts predicted to enter the market by the model estimated in Step 2.[30] Results show that both variable and fixed costs are important. Eliminating variable costs (while keeping fixed costs) produces 33-45 percent of the trade volume, and 55-75 percent of the gains, as eliminating

[30] Only 13 districts enter in the wet year, 27 in the median year, and 43 in the dry year.

both variable and fixed costs.[31] Results also suggest that the majority of the potential gains from trade can be attained by relatively few market participants.

Without conveyance costs. I also investigate the consequences of purely physical conveyance costs. How much more trade would occur if water could be traded costlessly? Scenario 4 simulates an efficient market with all transaction costs c_{kl} set to zero, implausibly. More trading occurs, especially in non-dry years. Relative to Scenario 2, gains are about double in a dry year, at $1.2 billion, and triple in median and wet years. These results suggest that much of the observed dispersion in water valuations in different parts of California is unavoidable and due to the fact that water is costly to move.

Environmental constraints. Because my main scenario does not account for hydrological capacity constraints, it is natural to ask how important they might be. I focus on the most important juncture in California's hydrology, the Sacramento–San Joaquin Delta. Scenario 5 imposes the constraint that outflow from the Sacramento River may not increase, ensuring that additional trade of surface water does not harm water quality or fish migration. I implement this constraint by simulating markets separately within the Sacramento Valley and south of the Delta. Trading volumes and economic gains are very similar to Scenario 2 – the constraint barely seems to bind. The Delta is associated with large variable transaction costs, but if they mainly result from carriage losses, then they still show up in Scenario 2. This result suggests that most of the gains from a more efficient surface water market can be achieved without relaxing environmental regulations.

Functional form sensitivity. Last, I explore how sensitive my results are to the functional form for demand. Scenario 6 optimizes trade and evaluates gains using linear demand instead of isoelastic. Gains are lower than Scenario 2 by 9 to 28 percent, but the results are broadly similar. This suggests that the qualitative implications of my results are not driven by the choice of functional form.

[31] This does not imply that fixed costs are more important than variable costs, since a scenario that eliminated fixed but not variable costs might also achieve more than half the available gains.

8 Discussion and Conclusion

My main results estimate that the gains from trade available from reducing transaction costs in California's water market are $224 to $614 million per year, depending on water supply conditions. These estimates imply that the present value of legal and policy reforms that improve the allocative efficiency of water use across water districts could be around $12 billion.[32]

Are the potential gains large or small? I suggest they are moderate. On one hand, annual trading volumes would increase by two to three orders of magnitude, and the dollar value of benefits is considerable, so if the costs of achieving them are low, they are worth pursuing. On the other hand, only 10 to 15 percent of California's water consumption would change hands, and the gains from trade are no more than 2 percent of California's agricultural GDP or 4 percent of the state's water supply expenditures (Hanak et al. 2014).

Why might the potential gains be smaller than anecdotal evidence often suggests? One reason is that water is costly to move: The simulations without conveyance costs generate 2 to 3 times the gains, suggesting that much of the differences in water valuations across California are the inevitable result of physics. A second reason is that water demand is inelastic: Although there are vast differences in water valuations across districts, they can be arbitraged away with relatively little reallocation.

Another possibility is that the gains from trade among water districts are only a fraction of the total potential gains from water reallocation. My approach is relevant to realistic policy scenarios in which districts continue to control water rights. But a range of political economy and regulatory issues suggest that water districts may not accurately represent the preferences of their retail customers (Libecap 2005; Ayres and Bigelow 2022), potentially leading agricultural districts to overvalue water and urban districts to undervalue it. Addressing them would likely require more fundamental institutional reform to the structure of water districts or water rights. Alternatively, perhaps more of the gains are local (i.e., among farmers and households within districts) rather

[32] Calculated as a perpetual stream of the annual benefits, using a 3 percent discount rate and equally weighting wet, median, and dry year scenarios.

than statewide (between districts) and could be achieved through pricing reform and/or developing within-district water markets. Quantifying both possibilities is worth further study.

Which types of transaction costs matter most? There is strong support for both administratively-induced and policy-induced costs, and less support for delivery costs beyond the unavoidable conveyance costs. For delivery costs, variable cost estimates show that the San Francisco–San Joaquin Delta is a major barrier to trade. However, simulations indicate that its costs can be explained by necessary carriage losses, so there is not much evidence that pumping restrictions under the Endangered Species Act are a major barrier to trade on their own. There is also little evidence for other aspects of delivery costs, since delivery pathway characteristics tend not to get selected as determinants of variable costs.

For administrative-induced costs, the extensive-margin estimates and simulations suggest that fixed costs of market entry are generally high. Most districts never enter the market, preventing many beneficial transactions. Inexperience is an important barrier to trade, which is consistent with search, negotiation, and contracting costs. Even districts that face fewer regulatory reviews do not enter the market in a given year, suggesting that policy-induced costs do not explain all of the fixed costs. Administrative-induced costs can be reduced by building centralized exchanges, standardizing contracts, and increasing public information about transactions.

For policy-induced costs, there is strong evidence that regulatory reviews and approval processes are costly barriers to trade. They are large components of both variable and fixed transaction costs. It would not be desirable to eliminate all policy-induced costs, since regulatory reviews are important to prevent negative externalities. Instead, the costs of the externalities should be weighed against the benefits of the proposed transactions estimated here. In addition, there are likely many ways for the SWRCB, DWR, and USBR to reduce policy-induced costs without significantly exacerbating externalities, such as streamlining the review processes, combining reviews across agencies, creating more categories of exemptions for transactions that are small or otherwise unlikely to cause significant negative externalities, expanding water-use monitoring systems, and producing standardized estimates of consumptive-use fractions.

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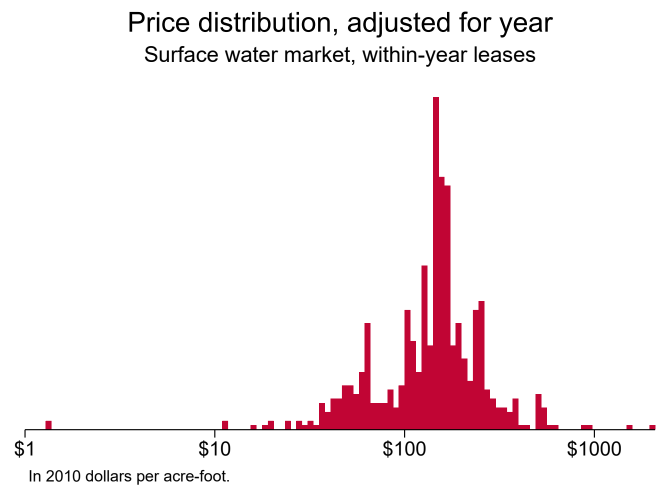
Figures

(a)



(b)

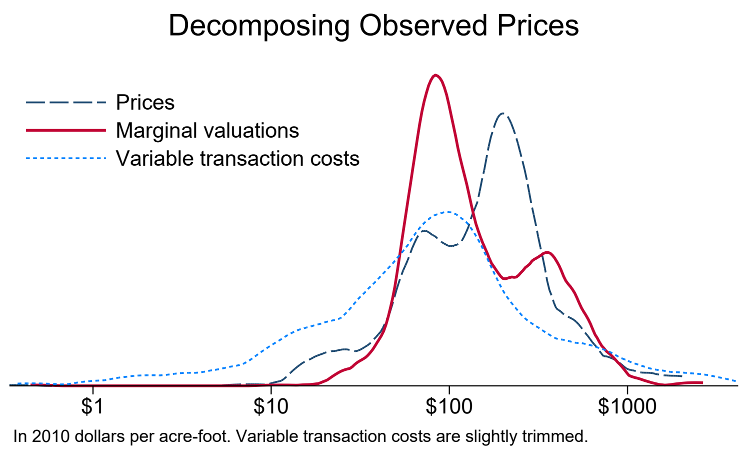


Figure 1: Panel (a): Distribution of surface water transaction prices in the data used for analysis, controlling for year, logarithmic scale. Observations are transactions of within-year leases of surface water observed in California, 1992-2015. The overall sample mean is added to the residual from a regression of log price on year fixed effects. Panel (b): Kernel density estimates of observed prices and estimated marginal valuations for the same transactions, logarithmic scale. Observations are surface water transactions made by each water district. [Back]

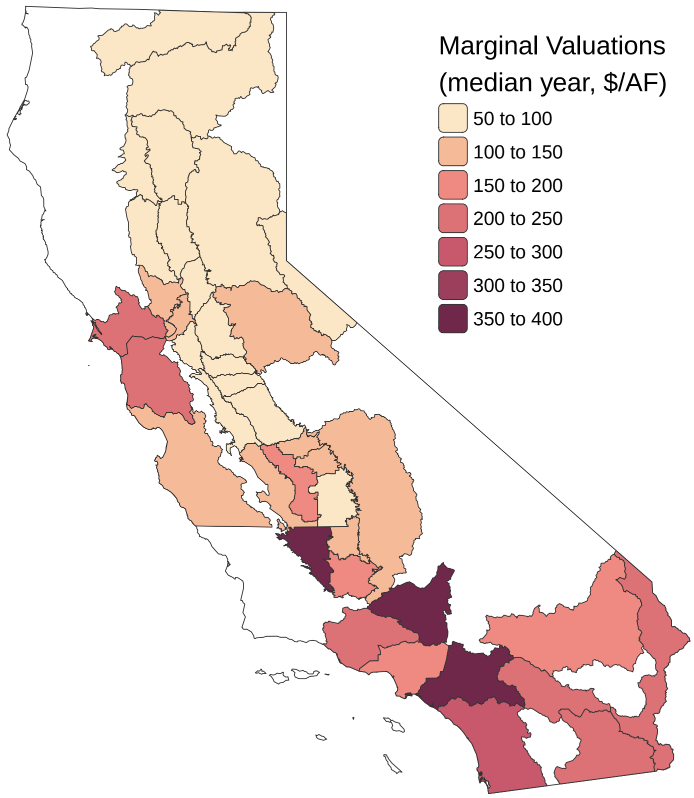


Figure 2: Mean estimated marginal valuations (per acre-foot) by planning area for a median-year scenario. Planning areas are geographical regions defined by the California Department of Water Resources; unshaded areas have no transactions observed in the data. Estimates are obtained by evaluating the demand model at quantities observed in 2010, the year chosen to represent the median-year scenario. Means are taken over districts, weighting by surface water quantity consumed. [Back]

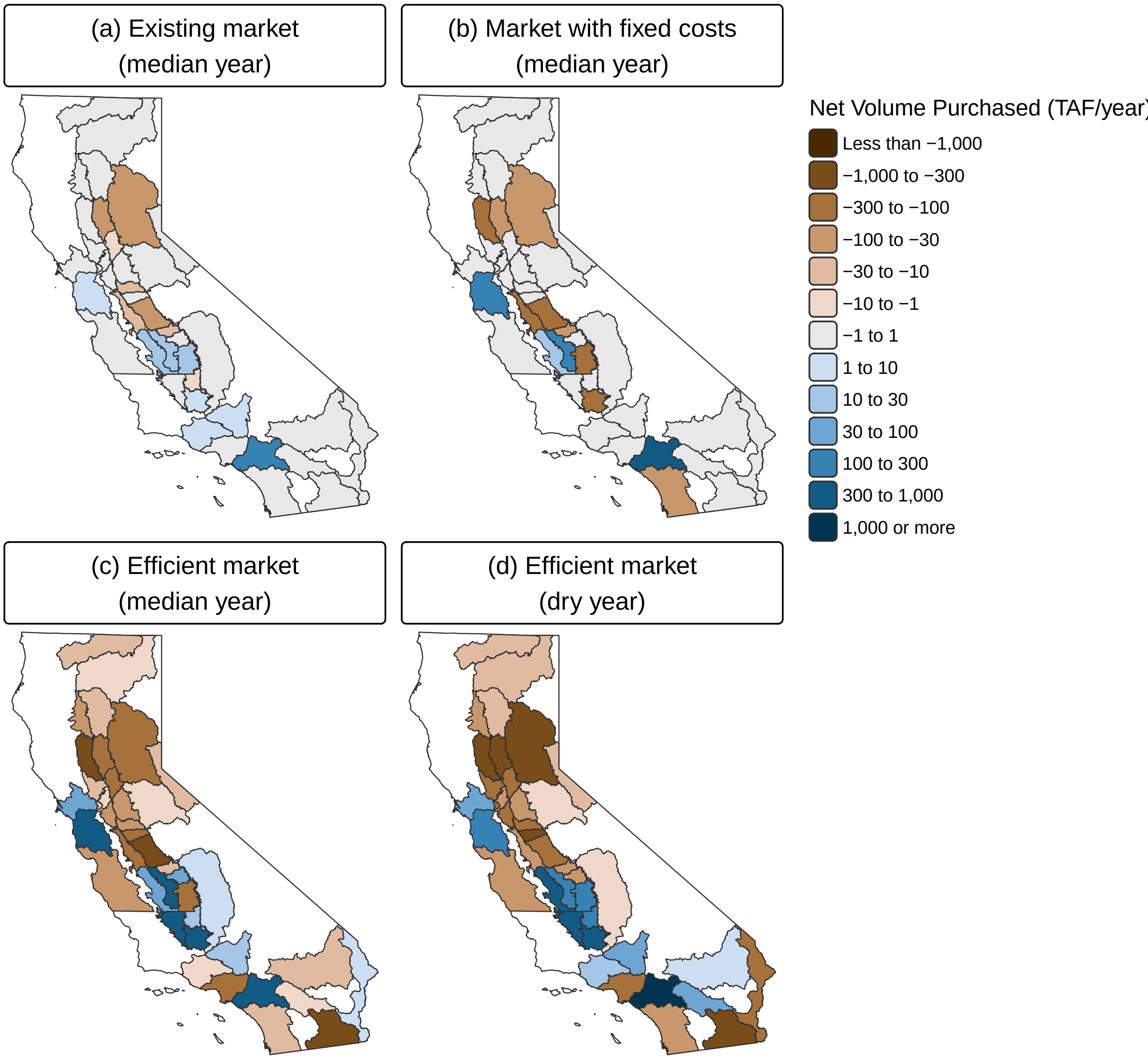


Figure 3: Net annual surface water quantities traded (TAF = thousand acre-feet) in observed transactions (Scenarios 1-2) and additional quantities traded in counterfactual simulations (Scenarios 3-4), by planning area. The efficient market scenarios use the estimated demand model to maximize aggregate surplus, subject to physical conveyance costs calibrated from a hydrological network model. The fixed cost scenario does the same, with trading restricted to districts predicted to enter the market. [Back]

Tables

Table 1: Transactions data

Panel A: Summary statistics

Variable	Mean	SD	Obs.
Volume (acre-feet)	9,571.7	28,224.7	1248
Price (2010$/acre-foot)	235.5	297.6	1259
Distance conveyed (km)	206.1	269.7	1247
Distance conveyed in rivers (km)	80.0	103.1	1247
Distance conveyed in canals (km)	126.0	203.8	1247
Distance of virtual conveyance (km)	86.4	118.5	1247
Elevation lift (ft)	421.5	1,029.5	1247
Crosses the Sacramento-San Joaquin Delta (=1)	0.27	0.444	1247
Reviewed by the State Water Boards (=1)	0.411	0.492	1259
Within project (=1)	0.422	0.494	1259

Panel B: Transactions by sector

	Sales		Purchases		Net Sales
	Count	Volume (TAF)	Count	Volume (TAF)	Volume (TAF)
Agricultural	639	7,130.4	330	1,785.9	-5,344.5
Urban (Municipal & Industrial)	100	819.3	190	2,209.9	1,390.6
Panel C: Transactions by hydrologic region					
Central Coast	27	18.5	33	18.7	0.2
Colorado River	20	824.4	6	69.5	-755.0
North Coast	2	3.7	2	0.7	-2.9
Sacramento River	275	4,219.5	37	89.5	-4,130.1
San Francisco Bay	16	188.6	46	530.1	341.5
San Joaquin River	298	2,088.2	104	576.6	-1,511.6
South Coast	10	154.3	68	1,573.3	1,419.0
South Lahontan	2	14.4	30	11.1	-3.2
Tulare Lake	89	438.2	194	1,126.3	688.1

Dataset of spot-market transactions (i.e., within-year leases) of surface water in California made by each district (so transactions are repeated for each party). Panel A reports summary statistics of transaction characteristics. Panels B and C reports the count and total volume of transactions sold and purchased in each sector or hydrologic region. Net sales within category do not sum to zero because inclusion criteria are applied separately to each side of a transaction (e.g., many agricultural sales are purchased by environmental or government entities, which do not appear in the table as buyers). TAF = thousand acre-feet.

Table 2: Variable Transaction Costs from Observed Determinants (Step 1)

	Dependent variable: Log Price					
	All determinants			Lasso-selected determinants		
	(1)	(2)	(3)	(4)	(5)	(6)
Seller × River dist. (km, 1000s)	–0.81	–0.84	0.22			0.45
	(0.76)	(0.63)	(0.60)			(0.64)
Seller × Canal dist. (km, 1000s)	–0.31	–0.30	0.042			
	(0.68)	(0.73)	(0.80)			
Seller × Virtual dist. (km, 1000s)	–0.73	–0.68	–0.50			
	(0.47)	(0.50)	(0.44)			
Seller × Pumping lift (ft, 1000s)	0.025	0.075	0.027			
	(0.10)	(0.10)	(0.12)			
Seller × Delta crossing (=1)	1.0***	0.94***	0.42	0.66***	0.68***	0.31
	(0.26)	(0.27)	(0.30)	(0.14)	(0.20)	(0.20)
Seller × State Boards review (=1)	0.53**	0.51**	–0.055	0.59**	0.49*	
	(0.22)	(0.23)	(0.27)	(0.26)	(0.26)	
Seller × Import into project (=1)	–0.0079	0.095	0.058			
	(0.064)	(0.091)	(0.059)			
Seller × Export from project (=1)	0.39***	0.28*	0.35	0.31***	0.26*	
	(0.13)	(0.17)	(0.28)	(0.096)	(0.14)	
Seller × Ag counterparty (=1)	0.0034	0.061	0.25***			0.20**
	(0.096)	(0.11)	(0.079)			(0.080)
−Buyer × River dist. (km, 1000s)	–0.91	–0.71	–0.65			
	(0.59)	(0.53)	(0.50)			
−Buyer × Canal dist. (km, 1000s)	–0.48	–0.15	0.25			
	(0.66)	(0.72)	(0.66)			
−Buyer × Virtual dist. (km, 1000s)	0.095	0.017	–0.23			
	(0.36)	(0.49)	(0.32)			
−Buyer × Pumping lift (ft, 1000s)	–0.20*	–0.26*	–0.36***			
	(0.11)	(0.14)	(0.13)			
−Buyer × Delta crossing (=1)	0.28	0.22	0.17			
	(0.21)	(0.16)	(0.17)			
−Buyer × State Boards review (=1)	0.31**	0.31**	0.30**			0.17**
	(0.13)	(0.14)	(0.13)			(0.076)
−Buyer × Import into project (=1)	–0.31**	–0.26**	–0.13			
	(0.14)	(0.13)	(0.10)			
−Buyer × Export from project (=1)	0.56***	0.55***	0.54***		0.48	0.45**
	(0.20)	(0.21)	(0.19)		(0.31)	(0.22)
−Buyer × Ag counterparty (=1)	–0.20	–0.21*	–0.16			
	(0.12)	(0.12)	(0.13)			
Side × District FE	✓	✓		✓	✓	
Side × Hydro. region × Year FE	✓			✓		
Side × Planning area × Year FE		✓			✓	
Side × District × Year FE			✓			✓
Observations	1,247	1,247	1,247	1,247	1,247	1,247
Observations excluding singletons	1,032	966	689	1,032	966	689
Clusters	113	105	76	113	105	76

Regressions of transaction price on observable cost determinants. Observations are transactions made by each water district, stacked such that each transaction is repeated for each district involved. Cost determinants are interacted with the district's side of the market (buyer or seller). On both sides of the market, positive coefficients indicate positive transaction costs. Seller-side coefficients compare prices across buyers, so a positive coefficient reflects a price premium. Buyer-side coefficients compare prices across sellers, but regressors are multiplied by −1, so a positive coefficient reflects a price discount. California is divided into 10 hydrological regions and 56 planning areas. Standard errors in parentheses are clustered by transaction and district. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 3: Market Entry and Inverse Price Elasticity of Demand (Steps 2-3)

	(1)	(2)	(3)	(4)
	Probit	First stage	Reduced form	IV Lasso
	Any Trades	Log Quantity	Adjusted Log Price	Adjusted Log Price
Log quantity consumed				–1.4**
				(0.45)
Log allocation %, own	–0.0029	0.16***	–0.12	
	(0.037)	(0.046)	(0.076)	
Log allocation %, rest of state	–1.9***	0.96***	–3.1***	
	(0.43)	(0.29)	(0.94)	
Inverse Mills ratio		–0.0077	–0.055	–0.11
		(0.027)	(0.061)	(0.068)
Any trades, year $t-1$	0.74***			
	(0.093)			
Any trades, year $t-2$	0.95***			
	(0.12)			
Any trades, year $t-3$	0.27***			
	(0.091)			
Any trades, sum of prior years	0.13***			
	(0.019)			
Log maximum water rights	0.21***			
	(0.021)			
Central Valley Project (=1)	0.54***			
	(0.078)			
State Water Project (=1)	0.87***			
	(0.15)			
Allocation variables (lasso-selected)	✓			
District fixed effects		✓	✓	✓
Linear time trend		✓	✓	✓
Observations	54,498	972	972	972
Clusters	2,355	155	155	155
Pseudo-R^2	0.59			
Lasso-selected instruments				3
First-stage F-statistic		13		46
Sup-score weak-ID test				reject

Observations are transactions made by each water district. Column (1) reports pooled probit estimates of the extensive-margin decision of market entry (i.e., the probability of any surface water transactions); the data also includes years when districts do not trade and districts that never trade. Columns (2) and (3) report first-stage and reduced-form effects of two allocation instruments on quantity consumed (of surface water) and marginal valuations (i.e, prices adjusted for variable transaction costs estimated in Step 1). Column (4) reports instrumental variable lasso estimates of the elasticity of marginal valuations with respect to quantity consumed, using the full set of candidate instruments. Columns (2)-(4) correct for sample selection using an inverse Mills ratio estimated from year-specific versions of the model in column (1). Standard errors in parentheses are clustered by district in column (1) and calculated by Bayesian bootstrap with weights blocked by district in columns (2)-(4). * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 4: Annual Economic Gains from Surface Water Markets

Panel A: Observed Transactions in the Existing Market					
Conditions	Volume traded (TAF)	Average marginal valuation ($/AF)			Gains (millions)
Scenario 1. Observed market (spot market transactions)					
Dry	123	$ 284			$ 54.8
Median	289	$ 161			$ 8.3
Wet	35	$ 129			$ 1.5

Panel B: Simulated Markets Without Transaction Costs					
Conditions	Additional volume traded (TAF)	Average equilibrium price ($/AF)	Gains (millions)		
			From lower costs of observed transactions	From new transactions	Total
Scenario 2: Efficient market (with only physical costs of conveyance)					
Dry	4,019	$ 172	$ 83.3	$ 531.0	$ 614.3
Median	3,347	$ 134	$ 44.3	$ 187.4	$ 231.7
Wet	3,639	$ 124	$ 4.3	$ 219.6	$ 223.9
Scenario 3: With fixed transaction costs					
Dry	1,826	$ 237	$ 71.4	$ 388.0	$ 459.4
Median	1,191	$ 161	$ 38.8	$ 89.6	$ 128.4
Wet	1,191	$ 129	$ 2.7	$ 138.8	$ 141.6
Scenario 4: No conveyance costs					
Dry	4,714	$ 205	$ 93.5	$ 1,100.0	$ 1,193.5
Median	4,990	$ 165	$ 81.9	$ 636.6	$ 718.5
Wet	5,287	$ 151	$ 11.0	$ 722.4	$ 733.3
Scenario 5: With a key environmental constraint (Sacramento River outflow held fixed)					
Dry	3,571	$ 178	$ 67.3	$ 538.4	$ 605.7
Median	3,120	$ 136	$ 43.2	$ 185.7	$ 228.8
Wet	3,425	$ 125	$ 3.9	$ 214.0	$ 218.0
Scenario 6: Linear demand (instead of isoelastic)					
Dry	2,669	$ 133	$ 80.5	$ 360.2	$ 440.7
Median	2,818	$ 114	$ 51.0	$ 160.3	$ 211.3
Wet	2,982	$ 105	$ 2.5	$ 167.1	$ 169.6

Per-year welfare analysis of the existing market (Panel A) and counterfactual simulations (Panel B). Each scenario is run under dry, median, and wet conditions, which draw quantities and trading volumes from the years 2014, 2010, and 2006, respectively. All dollar figures are in 2010 USD; gains are per year. TAF = thousand acre-feet.

A Online Appendix: Tables and Figures

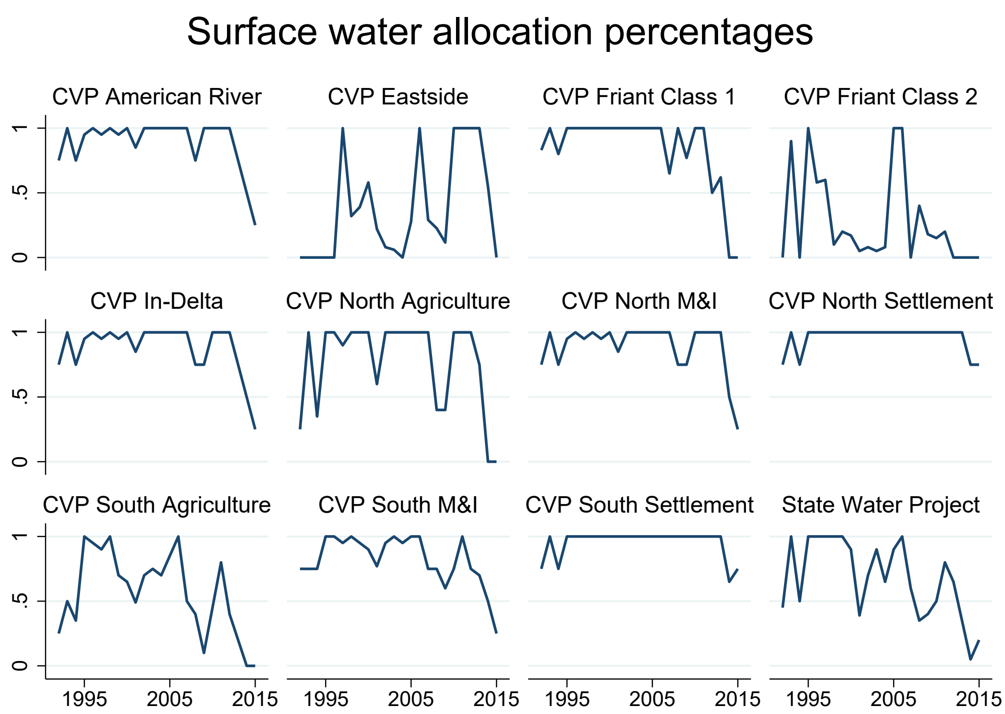


Figure A1: Variation over time in allocation percentages for each category of contracts with the federal and state water projects (CVP = Central Valley Project, M&I = Municipal & Industrial). These allocation percentages are used as instruments to estimate demand elasticities. This figure combines agricultural and municipal contracts in the State Water Project because they are equal during the years used in analysis. [Back]

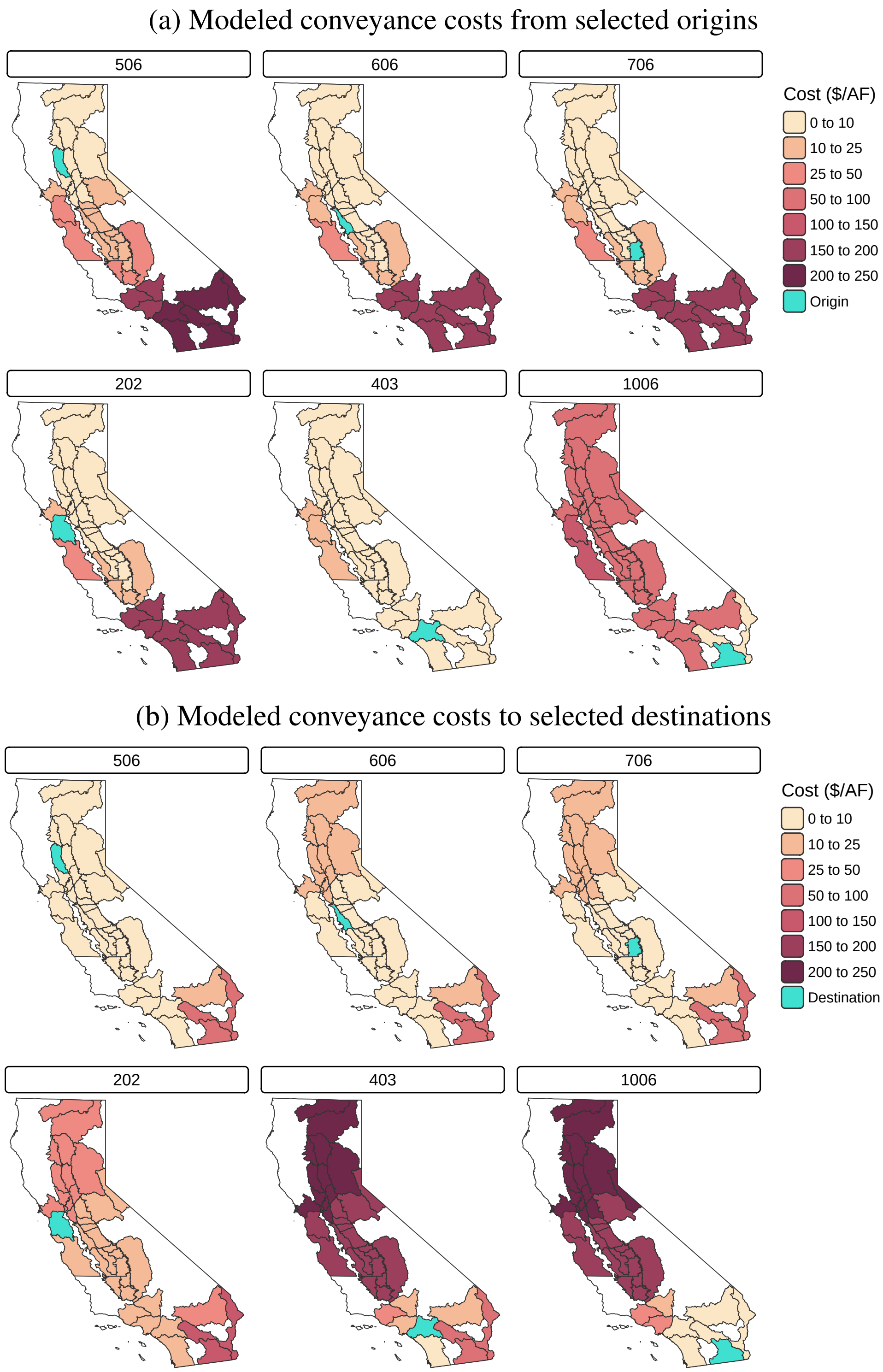


Figure A2: Conveyance costs in the hydrologic network model used in simulations. Panel (a) shows costs of transporting water from selected origins (in turquoise) to all other planning areas in the data; Panel (b) shows costs of transporting water to selected destinations from all other planning areas. The six origins/destinations selected for these maps are representative planning areas within each of the six hydrological regions with the most water consumption.

Table A1: Inverse Price Elasticity of Demand: Robustness Checks

	Adjusted log price				Unadjusted	Adjusted
	(1)	(2)	(3)	(4)	(5)	(6)
Log quantity consumed	–1.9***	–1.6***	–1.4**	–1.5**	–1.5**	–0.93*
	(0.48)	(0.45)	(0.61)	(0.45)	(0.48)	(0.51)
Inverse Mills ratio	–0.24**	–0.11	–0.12		–0.092	–0.18
	(0.066)	(0.073)	(0.069)		(0.063)	(0.067)
District fixed effects	✓	✓	✓	✓	✓	✓
Linear time trend		✓	✓	✓	✓	✓
Planning area X time trend	✓					
Year fixed effects						✓
Candidate instruments	All	Overall	Regional	All	All	All
Lasso-selected instruments	3	2	4	3	3	3
Observations	972	972	976	981	978	972
Clusters	155	155	156	155	156	155
First-stage F-statistic	53	50	39	47	50	13
Sup-score weak-ID test	reject	reject	reject	reject	reject	fail to reject

Instrumental variable lasso estimates of the inverse price elasticity of surface water demand. Observations are transactions made by each water district. Column (1) interacts the linear time trend with indicators for planning areas (56 geographic regions). Column (2) uses only the 3 overall water allocation instruments; column (3) uses only the remaining 130 region-interacted water allocation instruments. Column (4) omits the sample selection correction. Column (5) uses unadjusted prices as the dependent variable. Column (6) uses year fixed effects, which create spillover bias due to the joint determination of prices and quantities throughout the market. Standard errors in parentheses are calculated by Bayesian bootstrap with weights blocked by district. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A2: District Intercepts of Marginal Valuations (Step 4)

	Adjusted Log Price
Serves primarily municipal customers (=1)	0.17
	(0.12)
Central Valley Project contractor (=1)	–0.097
	(0.11)
State Water Project contractor (=1)	0.53***
	(0.15)
Lower Colorado contractor (=1)	0.73**
	(0.17)
Surface water rights holder (=1)	0.51***
	(0.095)
Log maximum water rights (centered)	–0.14***
	(0.039)
Latitude (degrees, centered)	–0.12*
	(0.061)
Constant	4.8***
	(0.14)
Var(District indicators)	0.55
	(0.25)
Var(District/counterparty pair)	0.35
	(0.068)
Var(Residual)	0.27
	(0.068)
Observations	965
Clusters	154

Random effects estimates of district and district-pair intercepts of marginal valuations (i.e., prices adjusted both for variable transaction costs estimated in Step 1 and the demand elasticity estimated in Step 3). Observations are transactions made by each water district. Standard errors in parentheses are calculated by Bayesian bootstrap with weights blocked by district. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A3: Variable Transaction Costs from Observed Determinants: Robustness Checks

	Dependent variable: Log Price					
	All determinants			Lasso-selected determinants		
	(1)	(2)	(3)	(4)	(5)	(6)
Seller × River dist. (km, 1000s)	–0.62	–0.95	–0.16			–0.25
	(0.60)	(0.62)	(0.72)			(0.51)
Seller × Canal dist. (km, 1000s)	0.094	–0.79	–1.2*			
	(0.52)	(0.73)	(0.65)			
Seller × Virtual dist. (km, 1000s)	–0.44	–0.18	–0.032			
	(0.51)	(0.45)	(0.47)			
Seller × Pumping lift (ft, 1000s)	–0.019	0.15	0.22*			
	(0.085)	(0.12)	(0.12)			
Seller × Delta crossing (=1)	0.77***	0.99***	0.55**	0.60***	0.73***	0.53**
	(0.16)	(0.19)	(0.24)	(0.13)	(0.15)	(0.22)
Seller × State Boards review (=1)	0.28	0.31	–0.019		0.29	
	(0.27)	(0.27)	(0.27)		(0.25)	
Seller × Import into project (=1)	0.11	0.11	0.0065			
	(0.15)	(0.15)	(0.075)			
Seller × Export from project (=1)	0.33*	0.36**	0.47*	0.47***	0.26	0.45***
	(0.17)	(0.17)	(0.26)	(0.13)	(0.18)	(0.13)
Seller × Ag counterparty (=1)	0.063	0.14	0.29***			0.22***
	(0.085)	(0.11)	(0.089)			(0.079)
−Buyer × River dist. (km, 1000s)	–0.48	–0.25	–0.43			
	(0.60)	(0.53)	(0.54)			
−Buyer × Canal dist. (km, 1000s)	–1.3	–1.5	–1.3	–1.2***	–1.4***	–1.0***
	(1)	(1.1)	(1.1)	(0.44)	(0.43)	(0.35)
−Buyer × Virtual dist. (km, 1000s)	–0.44	–0.51	–0.69**			
	(0.42)	(0.46)	(0.32)			
−Buyer × Pumping lift (ft, 1000s)	–0.032	–0.070	–0.15			
	(0.14)	(0.16)	(0.16)			
−Buyer × Delta crossing (=1)	0.19	0.22	0.26*			
	(0.15)	(0.15)	(0.15)			
−Buyer × State Boards review (=1)	0.11	0.086	0.0086			
	(0.084)	(0.086)	(0.066)			
−Buyer × Import into project (=1)	–0.23	–0.17	0.0059			
	(0.15)	(0.15)	(0.13)			
−Buyer × Export from project (=1)	0.22	0.19	0.011			
	(0.15)	(0.17)	(0.084)			
−Buyer × Ag counterparty (=1)	–0.12	–0.096	0.024			
	(0.12)	(0.13)	(0.14)			
Side × District FE	✓	✓		✓	✓	
Side × Hydro. region × Year × Month FE	✓			✓		
Side × Planning area × Year × Month FE		✓			✓	
Side × District × Year × Month FE			✓			✓
Observations	1,233	1,233	1,233	1,233	1,233	1,233
Observations excluding singletons	951	863	605	951	863	605
Clusters	104	97	67	104	97	67

Regressions of transaction price on observable cost determinants, as in Table 2. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

B Online Appendix: Theory and Estimation

B.1 Motivating no-arbitrage

Each district is comprised of a continuum of consumers whose preferences are aggregated to the district's demand function. Spatial arbitrage across districts is conducted by two layers of intermediaries, which might be thought of as brokers representing each district. In each district, selling intermediaries ("sellers") can buy units of water from consumers (at their marginal valuations V_j) and sell to buying intermediaries ("buyers") in another district. Buyers, in turn, buy water from sellers and can sell to consumers in their own district (at their marginal valuations V_k). Sellers and buyers meet at exchange points unique to each pair of districts, where prices p_{ijk} are determined. (In this section I suppress time subscripts.)

Assumption 6 (Perfect competition)**.** *Each district has enough intermediaries that they behave as price takers. That is, the quantity sold q^s_{ijk} or purchased q^b_{ijk} by any one intermediary does not affect the equilibrium price for any district pair: $dp_{ijk}/dq^m_{ijk} = 0$ for all j and k.*

Sellers and buyers choose non-negative quantities for each buyer-seller pair jk to maximize net profits:

$$\begin{aligned} &(Sellers) \quad \max_{q^s_{ijk}} p_{ijk} q^s_{ijk} - V_j(Q_j) q^s_{ijk} \tau^s_{jk} \quad \text{s.t. } q^s_{ijk} \geq 0 \\ &(Buyers) \quad \max_{q^b_{ikj}} V_k(Q_k) q^b_{ikj} - p_{ikj} q^b_{ikj} \tau^b_{kj} \quad \text{s.t. } q^b_{ikj} \geq 0 \end{aligned} \tag{15}$$

Each problem has two candidate solutions. First, sellers and buyers may not trade at all. In order for trading quantities to be positive, there must be non-negative marginal surplus between the seller and buyer: $V_j(Q_j)\tau^s_{jk} \geq V_k(Q_k)/\tau^b_{kj}$. Second, if buyers and sellers do trade, first-order conditions yield the no-arbitrage condition in Equation 3.

B.2 Identification assumptions for Step 3

Besides the sample selection, this step has two key identification assumptions. One is conditional independence: changes in allocation percentages are not correlated with any other time-varying factors that independently affect prices or quantities. The other is the exclusion restriction: changes in allocation percentages affect prices only through movements along demand curves, not through shifts in demand curves. Conditional independence ensures that the first stage and reduced form relationships are free from omitted variables bias, and the exclusion restriction ensures that the IV estimate can be interpreted as a causal relationship.

Conditional independence is a plausible assumption. Unit fixed effects absorb the influence of typical water availability, so the elasticity is estimated using only year-to-year variation in allocation percentages. In a different setting, local weather patterns might be an omitted variable, but in California, local rainfall meets a vanishingly small proportion of water demand. If a unit's own allocation percentage were the only instrument, another omitted variable might be water supplies in other parts of the state, since they are correlated and can all affect equilibrium outcomes, but I avoid this problem by using the full set of allocation percentages as instruments for prices faced by each unit.

The exclusion restriction is also plausible in this setting. Allocation percentages are pure supply shocks. Increasing one unit's surface water allocation will increase quantities and decrease equilibrium prices, moving along demand curves without changing underlying preferences. Increasing other units' allocations will lower their marginal valuations, raising quantities traded, decreasing equilibrium prices and again increasing the first unit's quantity. Substitution to groundwater or storage does not violate the exclusion restriction, which simply requires that any allocations-driven changes in quantities also be reflected in prices.[33]

[33] A decrease in surface water endowments may lead a unit to extract more groundwater, reducing surface water quantity by less than would occur otherwise. In a simple model, agents extract groundwater until the marginal cost equals the marginal valuation of water. Suppose the cost of groundwater extraction does not depend on surface water endowments, and groundwater is perfect substitute for surface water in the short run. Under these plausible conditions, year-to-year changes in groundwater quantities are fully determined by changes in the marginal valuations of water, and they need not enter demand as a separate term. Estimated elasticities measure the response of market prices to surface water quantities, net of any groundwater extraction response.

C Online Appendix: Proofs

C.1 Year effects bias elasticity estimates when comparing within a common market

Year effects introduce bias by comparing across units within the same water market. Trade creates mechanical spillovers: changes to any one unit's prices and quantities alter the equilibrium and affect the prices and quantities of others, violating the stable unit treatment value assumption (SUTVA). The intuition is that within a single interconnected market, year effects difference out statewide average prices and quantities, but these averages are themselves endogenous.

To keep the proof as simple as possible, I focus on the first-stage relationship, showing that the effect of the instrument on quantities is biased. Consider a regression of quantities on prices estimated by two-stage least squares with a single instrument. Because the two-stage least squares (2SLS) estimate is equal to the ratio of the first-stage and reduced form coefficients, if the reduced form is biased, the 2SLS estimate is also biased.

Consider a simple data generating process involving two agents. In each year, each agent receives a fixed quantity α_i plus an observed time-varying endowment z_{it}, of which they keep a fraction β and trade away the remainder to the other agent. Each agent also consumes an idiosyncratic shock ε_{it} that is uncorrelated with endowments. Total quantities are:

$$q_{1t} = \alpha_1 + \beta z_{1t} + (1-\beta) z_{2t} + \varepsilon_{1t} \qquad \mathbb{E}[\varepsilon_{1t} | z_{1t}, z_{2t}] = 0$$

$$q_{2t} = \alpha_2 + \beta z_{2t} + (1-\beta) z_{1t} + \varepsilon_{2t} \qquad \mathbb{E}[\varepsilon_{2t} | z_{1t}, z_{2t}] = 0$$

This model captures a market with inertia; $\beta = 1$ would correspond to autarky while $\beta = 0.5$ would suggest no inertia, since endowments given to either agent would be allocated evenly. For simplicity, the model is linear and the coefficient β is constant across the two agents.

First, under this data generating process, a simple fixed effects regression that includes both endowments (each agent's own endowment and the other agent's endowment) would recover the correct, unbiased parameter β, because the econometric model would be identical to the data generating process.

Second, in general, a regression measuring the effect of agents' own endowment must also control for the other agent's endowment. An estimate of β from a regression containing only each agent's own endowment would suffer from omitted variables bias unless the other agent's endowment z_{-it} is uncorrelated with own endowment z_{it}.

Third, using year effects will produce a biased estimate of β. Consider the regression

$$q_{it} = \alpha_i + \beta z_{it} + \theta_t + v_{it}.$$

Year effects are incidental parameters, so they can be eliminated by differencing the two agents:

$$\begin{aligned}
(q_{1t} - q_{2t}) &= (\alpha_1 - \alpha_2) + \beta(z_{1t} - z_{2t}) + (\theta_t - \theta_t) + (v_{1t} - v_{2t}). \\
\Delta q_t &= \Delta\alpha + \beta\Delta z_t + \Delta v_t.
\end{aligned}$$

This is now a simple one-variable ordinary least squares model, so the coefficient estimate $\hat{\beta}$ can be expressed as a ratio of covariances:

$$\begin{aligned}
\hat{\beta} &= \frac{\operatorname{cov}(\Delta z_t, \Delta q_t)}{\operatorname{var}(\Delta z_t)} = \frac{\operatorname{cov}(\Delta z_t, q_{1t} - q_{2t})}{\operatorname{var}(\Delta z_t)} \\
&= \frac{\operatorname{cov}\big(\Delta z_t, (\alpha_1 + \beta z_{1t} + (1-\beta) z_{2t} + \varepsilon_{1t}) - (\alpha_2 + \beta z_{2t} + (1-\beta) z_{1t} + \varepsilon_{2t})\big)}{\operatorname{var}(\Delta z_t)} \\
&= \frac{\operatorname{cov}\big(\Delta z_t, (2\beta - 1) z_{1t} - (2\beta + 1) z_{2t}\big)}{\operatorname{var}(\Delta z_t)} = (2\beta - 1)\frac{\operatorname{cov}(\Delta z_t, \Delta z_t)}{\operatorname{var}(\Delta z_t)} = 2\beta - 1 \\
&= \beta - (1 - \beta)
\end{aligned}$$

which is not equal to β. Thus, year effects introduce a mechanical relationship such that the estimate $\hat{\beta}$ captures not only the correct effect of the endowment on the agent's own quantities (β), but also the effect of the endowment on the other agent's quantities $(1-\beta)$. In autarky ($\beta = 1$) there would be no market spillovers and $\hat{\beta}$ would be unbiased. In the no-inertia case of $\beta = 0.5$, the estimated effect would be zero – falsely suggesting that raising endowments does not increase quantities.

C.2 Solution to the planner's problem has the same necessary conditions as the market equilibrium

First, expand the first term of the maximand and rearrange it:

$$
\begin{aligned}
\sum_j \int_{Q_j}^{Q_j^f} V_j(\varphi)d\varphi &= \sum_j \exp\Big(-\eta\psi_j\Big)\Big(\eta+1\Big)^{-1}\big((Q_j^f)^{\eta+1}-(Q_j)^{\eta+1}\big) \\
&= \sum_j \exp\Big(-\eta\psi_j\Big)\Big(\eta+1\Big)^{-1}(Q_j)^{\eta+1}\left[\Big(\frac{Q_j^f}{Q_j}\Big)^{\eta+1}-1\right] \\
&= \sum_j \exp\Big(-\eta\psi_j\Big)\Big(\eta+1\Big)^{-1}(Q_j)^{\eta+1}\left[\Big(1+\frac{-\sum_{k>j}q_{jk}+\sum_{k<j}q_{kj}}{Q_j}\Big)^{\eta+1}-1\right].
\end{aligned}
$$

Then, take a first-order condition with respect to q_{od} by setting the derivative of the entire maximand equal to zero (assume district o sells to district d, without loss of generality):

$$
\begin{aligned}
0 &= \frac{d}{dq_{od}}\left\{\exp\left(-\eta\psi_o\right)\left(\eta+1\right)^{-1}(Q_o)^{\eta+1}\left[\left(1+\frac{-\sum_{k>o}q_{ok}+\sum_{k<o}q_{ko}}{Q_o}\right)^{\eta+1}-1\right]\right\} \\
&\quad+\frac{d}{dq_{od}}\left\{\exp\left(-\eta\psi_d\right)\left(\eta+1\right)^{-1}(Q_d)^{\eta+1}\left[\left(1+\frac{-\sum_{k>d}q_{dk}+\sum_{k<d}q_{kd}}{Q_d}\right)^{\eta+1}-1\right]\right\} \\
&\quad-\frac{d}{dq_{od}}\left\{\sum_{k>o}c_{ok}q_{ok}\right\} \\
&= \exp\left(-\eta\psi_o\right)\left(\eta+1\right)^{-1}(Q_o)^{\eta+1}\frac{d}{dq_{od}}\left(1+\frac{-\sum_{k>o,k\neq d}q_{ok}+\sum_{k<o}q_{ko}-q_{od}}{Q_o}\right)^{\eta+1} \\
&\quad+\exp\left(-\eta\psi_d\right)\left(\eta+1\right)^{-1}(Q_d)^{\eta+1}\frac{d}{dq_{od}}\left(1+\frac{-\sum_{k>d}q_{dk}+\sum_{k<d,k\neq o}q_{kd}+q_{od}}{Q_d}\right)^{\eta+1} \\
&\quad-c_{od}\frac{d}{dq_{od}}q_{od} \\
&= \exp\left(-\eta\psi_o\right)\left(\eta+1\right)^{-1}(Q_o)^{\eta+1}\left(\eta+1\right)\left(\frac{Q_o^f}{Q_o}\right)^{\eta}\frac{-1}{Q_o} \\
&\quad+\exp\left(-\eta\psi_d\right)\left(\eta+1\right)^{-1}(Q_d)^{\eta+1}\left(\eta+1\right)\left(\frac{Q_d^f}{Q_d}\right)^{\eta}\frac{1}{Q_d}-c_{od} \\
&= -\exp\left(-\eta\psi_o\right)\left(Q_o^f\right)^{\eta}+\exp\left(-\eta\psi_d\right)\left(Q_d^f\right)^{\eta}-c_{od}.
\end{aligned}
$$

Next, rearrange the demand model $Q_j^f = \left(V_j^f\right)^{\eta_j}e^{\psi_j}$ and substitute it for the parameters ψ_o and ψ_d:

$$
\begin{aligned}
0 &= -V_o^f\,(Q_o^f)^{-\eta}(Q_o^f)^{\eta}+V_d^f\,(Q_d^f)^{-\eta}(Q_d^f)^{\eta}-c_{od} \\
&= -V_o^f+V_d^f-c_{od}.
\end{aligned}
$$

Rearranging, and splitting transaction costs into seller and buyer components ($c_{od}=\tau_{od}^s+\tau_{od}^b$), the first-order conditions are:

$$V_d^f - V_o^f = \tau_{od}^s+\tau_{od}^b \quad \forall o,d \text{ s.t.} \quad q_{od}>0.$$

This is the no-arbitrage condition for the case of additive transaction costs.

C.3 Sum of district-specific gains equals the maximand

District-specific gains are defined as:

$$H_k \equiv \int_{Q_k^0}^{Q_k^f} \left[V_k(\varphi) - V_k(Q_k^f)\right] d\varphi. \tag{16}$$

I need to prove that the sum of district-specific gains in Equation 16 equals the maximand in Equation 14. The first term is identical in each expression, so it suffices to prove that the second terms are equal. Beginning with the second term of Equation 16 summed over all units j, I rearrange, switch indices twice, and expand:

$$\begin{aligned}
-\sum_j \int_{Q_j}^{Q_j^f} V(Q_j^f) d\varphi &= -\sum_j (Q_j^f - Q_j) V(Q_j^f) \\
&= -\sum_j \Big(-\sum_{k>j} q_{jk} + \sum_{k<j} q_{kj}\Big) V_j^f \\
&= \sum_j \sum_{k>j} q_{jk} V_j^f - \sum_j \sum_{k<j} q_{kj} V_j^f \\
&= \sum_j \sum_{k>j} q_{jk} V_j^f - \sum_k \sum_{j<k} q_{jk} V_k^f \\
&= \sum_j \sum_{k>j} q_{jk} V_j^f - \sum_j \sum_{k>j} q_{jk} V_k^f \\
&= \sum_j \sum_{k>j} q_{jk} (V_j^f - V_k^f) \\
&= \sum_j \sum_{k>j} q_{jk} \left[1(q_{jk} > 0) + 1(q_{jk} < 0)\right] (V_j^f - V_k^f) \\
& \quad \sum_j \sum_{k>j} q_{jk} \left[1(q_{jk} > 0)(V_j^f - V_k^f) + 1(q_{jk} < 0)(V_j^f - V_k^f)\right]
\end{aligned}$$

Inserting the first-order conditions from the previous proof (i.e., $V_d - V_o = c_{od}$ for all o and d such that $q_{od} > 0$):

$$\begin{aligned}
-\sum_j \int_{Q_j}^{Q_j^f} V(Q_j^f) d\varphi &= \sum_j \sum_{k>j} q_{jk} \left[1(q_{jk} > 0)(-c_{jk}) + 1(q_{jk} < 0) c_{kj}\right] \\
&= -\sum_j \sum_{k>j} q_{jk} \left[1(q_{jk} > 0) c_{jk} - 1(q_{jk} < 0) c_{kj}\right]
\end{aligned}$$

which is the second term of Equation 14.

D Online Appendix: Processing of Water Transactions Data

WestWater Research, LLC provided a dataset containing 6,264 water transactions in California between 1990 and 2015. Only a fraction of these transactions pertain to the surface water market; most are unrelated. Variables include date, volume, price, and duration of the transaction; type of water right the transaction is based on; and name and latitude and longitude of the origin and destination parties.

Cleaning. I calculate price per acre-foot and deflate to 2010 dollars using the CPI. I reshape the data so there is one observation per party per transaction, creating 12,975 observations. For transactions with multiple buyers or multiple sellers, if more specific information is not available, I divide transaction volume across parties in proportion to their maximum water rights.

Sample restrictions. To focus on transactions of actual surface water, I drop transactions of rights to pump groundwater within adjudicated basins, rights to store water in reservoirs or groundwater banks, and desalinated water. To focus on transactions in which the price is freely negotiated, I drop transactions within programs in which prices are set administratively. I drop one transaction that never cleared. This leaves 2,584 transaction-by-party observations from 1,104 unique transactions.

Location. I classify all observations into one of 10 hydrologic regions (defined by California's Department of Water Resources), and I generate latitude and longitude coordinates whenever possible. I first attempt to use centroids from my user location file, matching parties to users via my crosswalk file. This matches 1,827 transaction-by-party observations. Second, I manually geolocate 65 users that do not appear in the user location file but which are common in either transactions or water quantity data. For these users, I generate coordinates based on addresses, towns, or maps found via user websites and other publicly available documents; they match 222 additional observations. For remaining unmatched observations, I use location information from the original WestWater dataset; this assigns hydrologic region for all remaining observations and coordinates for 138 additional observations. This process leaves 398 observations for which hydrologic region is known but specific location coordinates are unavailable. Finally, I spatially join coordinates to 8-digit watershed (hydrological unit code, as defined by the U.S. Geological Survey), sub-sub-region (detailed analysis unit, as defined by DWR), and county. These shapefiles are available from DWR's California Water Plan: http://www.water.ca.gov/waterplan/gis/index.cfm.

Sector. I classify all parties into one of three sectors: agriculture, urban/municipal, or environmental. I use the first successful method in the following order of priority:

1. Water rights category (67% of observations). If the party appears in the surface water quantity dataset, I assign to agriculture or municipal depending on which sector holds a majority of the maximum water rights, including project contracts.

2. District associations and state and federal government agencies (20%). I classify as agricultural several known associations of agricultural water districts: San Joaquin River Group Authority, San Joaquin Water Conservation District, San Luis & Delta-Mendota Water Authority, Tehama-Colusa Canal Authority, Westside Districts, West Coast Basin Water Right Holders. I classify as environmental several state and federal agencies: California Dept. of Fish & Wildlife, California Dept. of Water Resources, Environmental Water Account, U.S. Bureau of Land Management, U.S. Bureau of Reclamation.

3. Keywords (9%). I classify users based on the following keywords in their name. Agriculture: almonds, citrus, contractors, dairies, dairy, famers, farm, farmers, farming, grower, irrigating, irrigation, nurseries, nursery, orchard, ranch, trust. Municipal: cement, cemetery, chemical, Chevron, church, city of, college, communities, community services, companies, company, corporations, developer, development, electric, energy, estate, gardens, golf, gravel, homeowners, homes, housing, inc., Indians, industries, investment, landscaper, leasing, LLC, LP, military, municipal, mutual water, non-ag, oil, owners, park, paving, power authority, properties, property, railway, real estate, realty, recycled, refining, replenishment

district, retail, sanitation, school, Texaco, town of, tribe, university, ventures. Environmental: conservancy, duck hunting, ducks, fish & wildlife, forest service, forestry & fire prevention, water bank.

4. Original use categories (4%). I apply WestWater's original water use categories, based on agriculture, irrigation, and environmental, counting all other categories as urban.

5. Remainder (1%). I assume remaining users called water districts are agricultural, and that all observations remaining after that are urban.

Characteristics of delivery path. I use the hydrologic model to calculate characteristics of the delivery path from buyer to seller. When there is more than one counterparty on the opposite side of the transaction, I define the delivery path by choosing the counterparty nearest to the geographic center of all the counterparties. For instream (environmental) transfers, I use the same location for the party and counterparty.