Regulatory Burden and Externalities in Surface Water Markets

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Abstract

Despite large potential gains from trade, surface water markets remain thin. The regulatory burden of acquiring information to manage heterogeneous hydrological externalities has been proposed to explain limited trade. To distinguish valuable regulation from inefficient transaction costs, I estimate a spatial model of California's surface water market incorporating agricultural production, urban demand, externalities, and regulatory constraints. Targeting trade externalities costs $29 per acre-foot, compared with $35 in average marginal external harm. I compare costly precise regulation with two policies that avoid trade-specific information: a uniform tax and a uniform performance standard. Under existing institutions, costly precise regulation outperforms either alternative. After broader market reform, a uniform performance standard becomes preferable, doubling baseline trade volumes. A uniform tax instead permits costly high-externality trades. Apparent transaction costs can be the price of effective regulation, and optimal regulatory design depends jointly on information costs, externality heterogeneity, and market institutions.

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1 Introduction

Water is a crucial input to economic activity, but markets for reallocating water remain remarkably limited. Globally, less than 1% of water claims are traded (Rafey, 2023). In California, limited market activity is especially striking because water prices vary enormously across users. Figure 1(a) depicts the distribution of water prices for agricultural and municipal users. Agricultural values vary substantially with groundwater access, and municipal values are typically much higher. Despite these potential gains from reallocation, surface water trade volumes account for only 1–5% of total surface water supply, as shown in Figure 1(b).

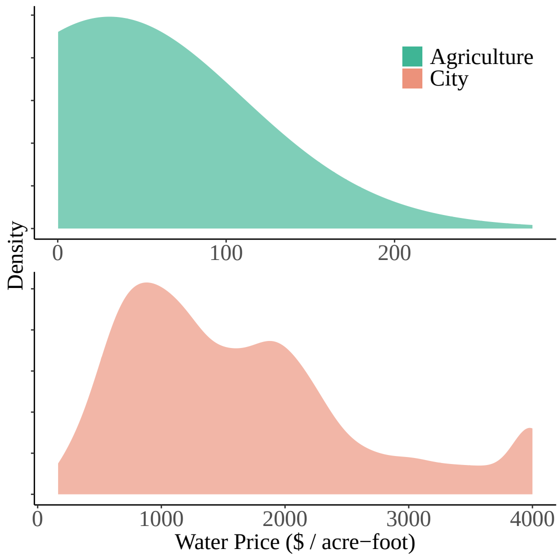
A central challenge is that surface water is not a conventional private good. Water diverted upstream contributes to downstream supply through return flows and transfers across the Sacramento–San Joaquin Delta can affect environmental flows, salinity, and endangered species. To ensure trade does not harm downstream users, water transfers face costly regulatory review and restrictions. These institutions can inhibit valuable trade, but do so precisely because trade imposes costs on third parties (Hagerty, 2023, Hanemann & Young, 2020, Leonard, Costello, & Libecap, 2019, Regnacq, Dinar, & Hanak, 2016, Young, 1986). This creates a basic challenge for market design. Observing that a regulation reduces trade does not imply that removing it improves welfare. Reduced trade can reflect a costly administrative friction, a socially valuable restriction on an externality, or both. Evaluating reforms requires separating the externalities created by trade, the restrictions used to mitigate them, and the costs of implementing those restrictions.

In this paper, I develop and estimate a spatial model of California's surface water market that separates the externalities created by trade, the restrictions used to mitigate them, and the additional costs of administering and completing transfers. This distinction matters for policy: removing a transaction cost can facilitate mutually beneficial trade, whereas removing a constraint that protects third parties can simply shift costs onto others.

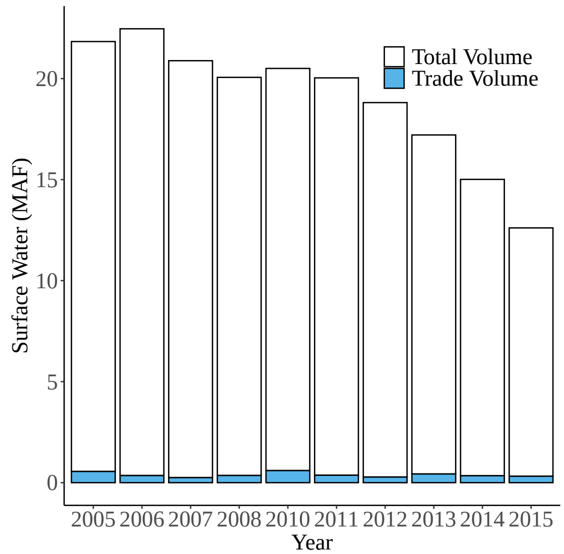
The setting provides a useful way to study a broader regulatory problem. When the externality created by an action varies across transactions, regulators can acquire transaction-specific information and target regulation accordingly, or economize on information using a common rule. The latter is cheaper to administer but regulates heterogeneous transactions identically. I use this tradeoff to compare existing transaction-specific regulation with a uniform tax and a uniform performance standard, and to study how their relative performance changes as other barriers to trade are removed.

To quantify these forces, I combine administrative data on surface-water supply and transfers, agricultural land and water use, groundwater pumping, urban utility demand, and hydrological connectivity. I estimate agricultural water values from crop and groundwater-pumping choices and urban demand from utility-level price and quantity data. I then embed these estimates in a bilateral trade model in which potential transfers depend on gains from trade, hydrological relationships, regulatory constraints, and buyer–seller-specific trade frictions. The estimated model allows me to evaluate reforms to rights administration, conveyance, and externality regulation while tracking both private gains and effects on third parties.

Figure 1: California's Water Price Dispersion and Limited Trade



(a) Water Prices by Use



(b) Total and Traded Surface Water Volume

Notes: Panel (a) shows distribution of prices per acre-foot for water from 2005-2015 for agricultural and municipal consumers. Agricultural prices are DAUCO-level marginal groundwater costs estimated in Section 6.1. City prices are average retail prices truncated at $4000. Panel (b) depicts surface water supply and trade in million acre-feet.

I find substantial unrealized gains from water trade. In dry years, the estimated market reallocates 357 thousand acre-feet (TAF), generating nearly $200 million in gains for agricultural and urban users, but estimated transaction costs absorb $137 million. Removing the cost associated with return-flow determination increases trade by 115 TAF, while reforming Delta conveyance increases it by 175 TAF. Implementing both reforms together increases trade by 357 TAF, approximately doubling baseline trade. More comprehensive reform of Delta conveyance, water rights, and return-flow determination increases trade by 644 TAF, bringing total dry-year trade to approximately one million acre-feet. These results show that the thinness of the market reflects several interacting barriers to exchange rather than a single dominant friction.

The return-flow regulation that restricts trade, however, also produces valuable information. The estimated cost associated with determining trade-specific return flows is $29.11 per acre-foot, while the average marginal external harm from return flows in the model is $35.20 per acre-foot. The cost of targeting these externalities is large, but so are the externalities that the information allows regulators to address. Making trade-specific return-flow information costless increases dry-year surplus by approximately $28 million under existing market institutions. Eliminating the cost of acquiring regulatory information is valuable; eliminating the information-intensive regulation itself is not.

I next ask whether regulators can avoid this information cost using simpler rules. I compare existing trade-specific regulation with a uniform tax and a uniform performance standard. For the latter, I focus on the least restrictive uniform standard that causes neither a loss of environmental water nor a reduction in water available to any downstream user. Under existing market institutions, costly precise regulation performs well relative to these coarse alternatives: paying to identify heterogeneous return-flow effects is worth the information it provides. The ranking changes, however, following broader market reform. After removing Delta and rights frictions, the uniform no-harm performance standard generates $81.5 million in additional surplus and 47.2 TAF of additional environmental water, compared with $69 million and approximately no change in environmental water under costly trade-specific regulation. In this environment, the simpler uniform rule becomes preferable to acquiring costly trade-specific information.

A uniform tax does not achieve the same result. I simulate a $35.20 per-acre-foot tax equal to the average marginal return-flow externality, which also avoids the need to determine trade-specific consumptive use. Following Delta and rights reform, the tax generates only $52.8 million in additional surplus and reduces environmental water by 15.9 TAF. Because the tax prices the average externality rather than restricting transfers according to their effects on downstream water, it remains too permissive of some high-externality trades. The uniform no-harm performance standard generates both greater surplus and greater environmental protection in the more liberalized market.

These results show that the appropriate regulatory technology depends on the broader institutions governing exchange. Precise regulation can justify its information costs when transaction-specific externalities are economically important. But precision is not always worth paying for: after broader market reform, a simpler performance standard can outperform costly trade-specific regulation. Nor does replacing information-intensive regulation with a uniform price necessarily solve the problem, because heterogeneity in externalities makes the average externality a poor guide to the harm from individual transactions. Apparent transaction costs can be the price of effective regulation, and the choice between coarse and precise regulation depends jointly on information costs, externality heterogeneity, and market institutions.

These findings connect the paper to three related literatures on water-market design, environmental regulation, and the measurement of water values.

First, I contribute to an active literature quantifying frictions and the gains from improved water-market design (Colby, 1990, Donna & Espin-Sanchez, 2018, Gupta, Hughes, & Wakerman Powell, 2018, Vaux & Howitt, 2018, Rafey, 2023). Ferguson & Milgrom (2024) and Leonard et al. (2019) emphasize the need to account for the interaction between transaction costs and externalities in water-market design. Closely related work by Regnacq et al. (2016) estimates how trade characteristics affect California water transfers using a similar dataset,[1] while Hagerty (2023) estimates and decomposes transaction costs in California's water market. I build on this work by distinguishing transaction costs from regulatory constraints that protect third parties from hydrological externalities. This distinction allows me to evaluate how market reforms interact with the design of externality regulation, rather than treating all observed barriers to trade as distortions.

Second, the paper contributes to a broader literature on environmental policy when regulatory instruments must be designed under uncertainty, heterogeneous damages, and costly information

[1] I am grateful to Ellen Hanak for sharing these data.

(Weitzman, 1974, Kolstad, 1987, Muller & Mendelsohn, 2009, Fowlie & Muller, 2019, Knittel & Sandler, 2018). This literature shows that uniform regulation can perform poorly when marginal damages vary across sources, while differentiated policies can improve targeting at the cost of greater informational requirements. California's surface water market provides a particularly useful setting for studying this tradeoff because detailed hydrological and market data allow me to quantify both heterogeneous trade externalities and the costs of regulating them. I show that the preferred externality regulation depends on other frictions governing the underlying market. More broadly, regulatory transaction costs may not be pure distortions; they can be the cost of acquiring information used to protect third parties.

Third, a large literature estimates models of crop choice (Carpentier, Letort, & Stenger, 2015, Carpentier & Letort, 2014, Scott, 2014), agricultural demand for groundwater (Burlig, Preonas, & Woerman, 2024, Ryan & Sudarshan, 2022, Timmins, 2002), and residential demand from water utilities (Arbués, García-Valiñas, & Martínez-Espiñeira, 2003, Worthington & Hoffman, 2008, Timmins, 2002). Recently, Rafey (2026) develops a detailed model of agricultural water values and water-right misallocation in California that accounts for heterogeneous crop production and long-lived capital investment. My agricultural model is deliberately more parsimonious, incorporating substitution between surface water and groundwater to estimate marginal water values that can be embedded in a model of trade across agricultural and urban users, hydrological externalities, and regulatory constraints.

The remainder of the paper proceeds as follows. Section 2 introduces the analytical framework. Section 3 describes California's surface-water institutions and the regulatory treatment of return flows, water rights, and Delta transfers. Section 4 presents the data and reduced-form evidence. Section 5 develops and estimates the model. Section 6 evaluates alternative market designs. Section 7 concludes.

2 Analytical Framework

This section provides a simple framework for distinguishing the externalities created by trade, the policies used to mitigate them, and the costs of implementing those policies. The distinction is useful in markets where transactions impose heterogeneous effects on third parties and regulators must acquire information to manage those effects.

There are $j = 1, \dots, J$ potential trading parties. Party j chooses an action $x \in X_j$ that generates private gains $G_j(x)$ and external harm $E_j(x)$. In the absence of regulation, the party chooses

$$x_j^0 \in \arg\max_{x \in X_j} G_j(x),$$

while the socially preferred action solves

$$x_j^* \in \arg\max_{x \in X_j} \{G_j(x) - E_j(x)\}. \quad (1)$$

A policy can affect this choice in two ways. It can impose a payment $T_j^p(x)$ on an action, or restrict the feasible action set to $X_j^p \subseteq X_j$. Implementing either policy may also impose a regulatory cost $C_j^p(x)$ through measurement, documentation, review, and compliance. Under policy p, the party chooses

$$x_j(p) \in \arg\max_{x \in X_j^p} \left\{ G_j(x) - T_j^p(x) - C_j^p(x) \right\}. \tag{2}$$

With costless information and administration, a regulator can tailor either prices or restrictions to the externality generated by a particular action. A transaction-specific tax can price the external harm directly, while a sufficiently precise performance standard can restrict the action so as to mitigate that harm. When transaction-specific externalities are costly to measure, however, regulation faces a tradeoff between targeting and administrative burden. A common tax may underprice high-externality actions and overprice low-externality actions, while a common performance standard may need to be sufficiently conservative to protect third parties across a heterogeneous set of actions.

This distinction also changes how regulatory frictions should be interpreted empirically. A regulation that restricts the amount or form of an action can reduce observed activity even if implementing the restriction is costless. An empirical model that attributes the entire resulting wedge to transaction costs confounds two economically distinct objects: the cost of implementing regulation and the protective restriction imposed by the regulation. Removing the former can increase private gains without weakening third-party protections; removing the latter can increase private gains while also increasing external harm.

More generally, the preferred regulatory design depends jointly on the distribution of private gains and externalities, the cost of acquiring transaction-specific information, and other frictions governing the market. These forces may not be separable. Other market frictions determine which actions occur and which externalities regulation must manage. Changing those frictions can consequently change the relative performance of coarse and transaction-specific regulation. Whether greater regulatory precision is worth its informational cost, and how that answer changes with the surrounding market institutions, are ultimately empirical questions.

This framework applies broadly to settings in which market activity creates heterogeneous third-party effects and regulation is itself costly to implement. The remainder of the paper applies it to surface-water markets, where these forces can be measured and where both protective restrictions and substantial costs of administering trade can be readily estimated.

3 Institutional Background

In this section, I describe the physical endowment and infrastructure for water in California, the system of property and usage rights, and provide a stylized example of how these features give rise to specific transaction costs and constraints on trade.

3.1 Water in California

Water in California supports the largest population and state agricultural economy in the United States. Total surface water use averaged 18.2 maf from 2005 to 2015. The majority comes from snowpack runoff that falls within the state.[2] There is a structural misallocation of surface water in California: two-thirds of water supply is in the north whereas two-thirds of demand is in the south (PPIC 2021). Because of this, there has been massive state, federal, and local investment in canal infrastructure, endowing California with one of the most advanced and interconnected water distribution systems in the world. Figure 2(a) maps the major rivers and canals in this system.

In Figure 2(b), I focus on the most important rivers and canals. The Sacramento River, beginning in the north, and San Joaquin River, beginning in the east, meet at the Sacramento–San Joaquin Delta in the middle of the state, just northeast of the San Francisco Bay. There are two major *projects*: the State Water Project (SWP) and the federally managed Central Valley Project (CVP). These water projects pool together rights to divert surface water and create a new water asset managed within project boundaries and distributed to project contractors. SWP contractors are largely urban wholesalers and utilities whereas CVP contractors are largely agricultural irrigation districts and farmers. The largest SWP and CVP canals export 1.5–6.7 maf annually out of the Delta through the California Aqueduct, Delta-Mendota Canal, and other routes (PPIC 2022).

The Delta is the critical nexus in California's water system, where abundant surface water supply meets project infrastructure that supplies 35% of statewide surface water use. Absent man-made diversion, 40% of the state's natural surface runoff flows through the Sacramento and San Joaquin Rivers, into the Delta, and then out into the San Francisco Bay. The Delta is where the Bay's saltwater meets freshwater outflow. If freshwater runoff into the Delta is too low or project exports are too high, more saltwater is drawn into the Delta, threatening endangered species, managed wetlands, local supply, and urban and agricultural exports.[3] Accordingly, there are important physical and regulatory constraints on water transferred across the Delta.

3.2 Water Rights and Trade

To manage this large, interconnected, and volatile system, California allocates usufructuary property rights to divert surface water directly from rivers.[4][5] Right holders are entitled to a maximum annual quantity in order of seniority, determined by the date at which diversion began. Surface water rights

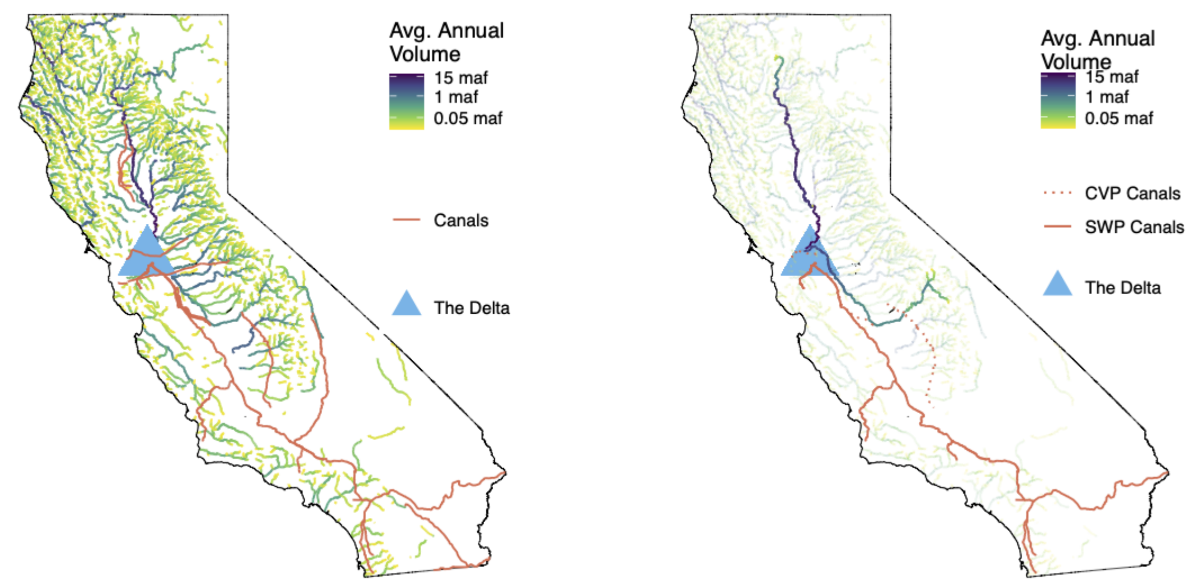
[2] Intrastate supply is supplemented with 4.4 maf of Colorado River imports. Colorado River water is imported through the Colorado River Aqueduct and All-American Canal depicted in Figure 2.

[3] There are additional restrictions on project exports to protect fish species affected by pumping operations (PPIC 2022).

[4] Usufructuary rights are rights to *use* the resource, rather than rights to *own* particular units of it. Since water is a flowing resource, these rights differ from ownership of physical property such as land (Thompson, Leshy, & Abrams, 2013).

[5] There are both riparian and appropriative property rights in California, along with other water-right types. Throughout the paper, I mean appropriative property rights when I refer to surface water rights, as these make up the majority of water use in the state and have an organized process and clear legal right to transfer (Thompson et al., 2013).

Figure 2: California Surface Water System



(a) All Rivers and Large Canals

(b) Key Rivers and Project Canals

Notes: Panel (a) depicts all streams and major canals in California and indicates average annual flows from 1970-2000 using data from NHD Streamflow V2. Panel (b) highlights the Sacramento and San Joaquin Rivers, the major State Water Project and Central Valley Project canals, and the confluence at the Delta.

specify a seniority date, maximum annual volume, maximum rate of diversion, point of diversion, place of use, and purpose of use.[6]

These diversion rights are incomplete property rights in the sense that they do not explicitly clarify all the information necessary for trade. In particular, rights do not specify the annual quantity available to the user or the degree to which the user's diversion contributes to downstream supply. These quantities instead have to be determined when a transfer is proposed.

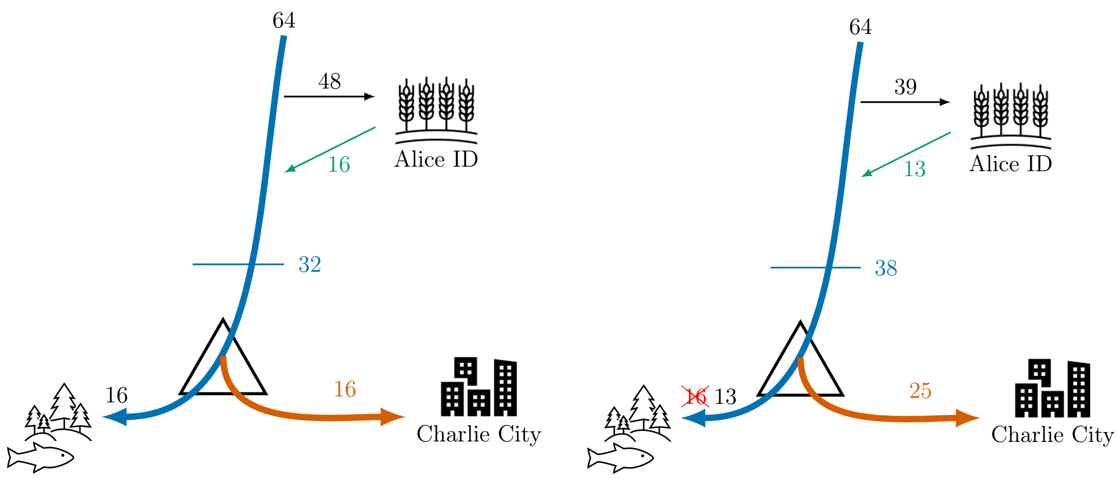
A key feature of surface water management is that a single molecule of water can be diverted by multiple users before being lost to evaporation or transpiration (Young, 1986). For example, when a farmer diverts water from a stream to irrigate fields, water not evapotranspirated[7] can enter the watercourse downstream as *return flow*, either through runoff or groundwater percolation (Chong & Sunding, 2006). A downstream user may then divert that same water. While a right holder's annual

[6]These details are right-specific and generally cannot be changed without administrative approval, yielding a highly heterogeneous set of commodities.

[7]Evapotranspiration is the joint process by which water evaporates and is transpired by plants.

quantity and contribution to downstream supply are important for managing trade, neither is listed ex ante and both may need to be determined at a cost when a transfer is proposed. Transfers that fail to account for these downstream contributions can harm other users or environmental flows.

Figure 3: Example of Return Flow Dependence and Trade



(a) Baseline Allocation (b) Transfer Externality

Notes: Figure presents a stylized example of return flow contributions to supply and potential externalities from surface water transfers. Panel (a) shows a representative baseline example. Diversions are in black and return flow contributions are in green. Panel (b) depicts the consequences of a trade of 9taf from Alice to Charlie that does not properly incorporate return flow dependence.

Figure 3 provides a stylized example of how transfers can create third-party externalities and how California manages them. Panel (a) presents a stream with 64 thousand acre-feet (taf) of surface water annually. Alice Irrigation District diverts 48 taf, Charlie City diverts 16 taf, and an additional 16 taf flows through the Delta and provides environmental services that mediate saltwater intrusion and sustain endangered species.

In total, there are three claims totaling 80 taf along a stream with only 64 taf of initial flow. These claims are feasible because they depend on return flow. When Alice applies 48 taf to her crops, she consumes two-thirds through evapotranspiration and 16 taf becomes return flow. Alice's *consumptive use* depends on crop choice, irrigation technology, climate, and hydrogeology.[8] Charlie City exports its water out of the Delta and returns nothing to the originating stream system.[9]

Suppose Charlie City has a much higher value for water than Alice and they agree to trade 9 taf. Figure 3(b) shows how this transfer can create a negative externality. Alice now applies 39 taf and returns only 13 taf downstream, while Charlie increases its diversion to 25 taf. Environmental flows consequently fall from 16 to 13 taf. Without careful management, a mutually beneficial trade between Alice and Charlie harms a third party.[10] Furthermore, because Charlie exports water

[8]While many production technologies and decisions affect consumptive use, most are not explicitly contracted on. Instead, rights restrict characteristics such as place and purpose of use that help stabilize return flows.

[9]Cities can also contribute return flow. Notably, Sacramento's urban use returns to the Sacramento River.

[10]These externalities can also affect other users along the stream. Typically, the burden falls on downstream users

through the Delta, the additional diversion can increase saltwater intrusion and affect endangered species. California takes three main steps to manage these issues.

Rights Verification: First, the seller must prove they have a right to surface water that year and verify the quantity available given hydrological conditions. The right specifies the maximum quantity the user can divert and where it can be used, but does not provide an annually updated quantity reflecting hydrological conditions and competing claims. In the stylized example, Alice must establish that at least 9 taf are available for transfer. Regulators and trading parties devote resources to verifying the quantity endowed by the right in a given year. Rights verification is primarily an informational transaction cost generated by incompletely specified property rights.

Return Flow Measurement and Adjustment: Once the quantity available to the seller is determined, regulators estimate the seller's consumptive use. Sellers provide information on recent crop production and irrigation practices, which is combined with agronomic models and other measurements to determine the anticipated reduction in consumptive use. The buyer is then restricted to diverting at most the seller's consumptive reduction so that the transfer does not reduce expected return flows. In the example, Charlie can divert only 6 taf because Alice consumes two-thirds of the 9 taf she leaves in the stream. The remaining 3 taf preserves Alice's expected return-flow contribution. This process has two conceptually distinct effects. Measuring Alice's consumptive share requires information and regulatory review, creating a transaction cost. The resulting adjustment from 9 taf to 6 taf is instead a restriction on the feasible transaction that protects downstream users. In the language of Section 2, it is a targeted performance standard. Distinguishing the cost of determining the adjustment from the adjustment itself will be important for evaluating alternative market designs.

Delta Constraints: To avoid saltwater intrusion, protect endangered ecosystems, and maintain the quality of project exports, transfers that cross the Delta must leave additional water—called *carriage water*—in the system as Delta outflow. On average, carriage water amounts to 22% of water made available by the seller. In the example, Charlie must leave 22% of the 6 taf made available after the return-flow adjustment as Delta outflow. Ultimately, Charlie can export only 4.68 taf out of the Delta. As with return-flow regulation, the carriage-water requirement should be distinguished from any administrative costs associated with satisfying it. The requirement itself reduces delivered quantities in order to protect Delta conditions. Regulatory review can impose additional transaction costs. Moreover, the underlying constraint is partly infrastructural. California is currently considering the Delta Conveyance Project, a pipeline that would divert water upstream on the Sacramento River and transport it directly south of the Delta.

Relationship to framework and empirical exercise. Each of these requirements can reduce observed trade, but for different reasons.[11] Rights verification primarily imposes an informational

that depend on return flows.

[11]Other frictions may also inhibit trade. Farmers may have limited experience with water markets and face uncertainty about transfer procedures, including concerns that selling water could jeopardize future rights under California's *use it or lose it* principle. Geographic distance can increase transportation and search costs, while

and administrative cost. Return-flow regulation combines the cost of determining consumptive use with a restriction on transferable quantities designed to preserve downstream supply. Delta management similarly combines regulatory and administrative costs with physical restrictions on delivered water.

These institutions map directly into the framework in Section 2. For a potential buyer–seller pair j, $G_j(x)$ is the surplus generated by reallocating surface water, while $E_j(x)$ captures the resulting effects on downstream users and environmentally sensitive flows. Return-flow adjustments and Delta carriage-water requirements restrict the feasible set X_j^p, while rights verification, consumptive-use determination, and regulatory approval contribute to $C_j^p(x)$. Other trading frictions also enter $C_j^p(x)$. The performance of alternative market designs depends on the joint distribution of gains from trade, hydrological externalities, regulatory costs, and other barriers across potential buyer–seller pairs.

Recovering these objects requires going beyond the relationship between regulatory requirements and observed trade. Existing quantitative analyses find that rights verification, return-flow determination, and Delta crossings predict substantially lower trade volumes (Regnacq et al., 2016, Hagerty, 2023), but do not separately model the quantity restrictions imposed to protect third parties. I combine a model of bilateral trade and hydrological externalities with variation in the requirements applying to different transfers. Water-right transfers require rights verification, whereas project-water transfers do not. Return-flow determination applies to rights transfers and project exports but not to transfers within a project, allowing project exports to inform the incremental friction associated with return-flow determination separately from that associated with rights transfers. Transfers crossing the Delta face both additional administrative requirements and carriage-water constraints. The model estimates these incremental trading frictions conditional on the protective and physical restrictions facing each potential pair.

The counterfactuals then vary these components separately. Rights reforms reduce the frictions associated with establishing and transferring entitlements, while Delta reforms relax both estimated Delta-crossing frictions and conveyance constraints. For return flows, I distinguish the cost of obtaining seller-specific information from the protection that information permits. I compare costly and costless seller-specific regulation with two policies that economize on transaction-specific information: a uniform tax and a uniform performance standard. These exercises allow the value of regulatory precision to vary with the other institutions governing trade.

4 Data

I combine administrative data on agricultural production, urban water use, hydrology, and observed water transfers to construct a panel of California's surface water market. The primary sample covers 2005–2015, with longer panels used to estimate particular components of the model. Together, these

agricultural-to-urban transfers can face political resistance because of concerns about exporting communities. I do not separately identify these mechanisms; the empirical model instead includes distance and residual buyer–seller-type frictions.

data allow me to measure the value of water across potential buyers and sellers, the hydrological relationships and regulatory restrictions associated with bilateral transfers, and the transactions that actually occur.

4.1 Water use and hydrology

Agricultural production and water use. The California Department of Water Resources (DWR) provides annual land and water use for 19 crop categories from 2002–2019 at the Detailed Analysis Unit by County (DAUCO) level. There are 281 DAUCOs with agricultural production tracked by DWR. For each DAUCO, crop, and year, I observe acres grown, applied water, effective rainfall, and evapotranspiration of applied water. DWR additionally estimates crop-specific evapotranspirative requirements based on local soil, climate, and other conditions. I combine these data with DAUCO-level surface water and groundwater supply from the DWR Water Balance to estimate agricultural production and the value of water in Section 7.

Groundwater. DWR reports groundwater-depth measurements from 43,659 wells across 515 groundwater basins. I use these measurements to construct annual groundwater depth at the DAUCO level from 2002–2019. I combine groundwater depth with regional electricity prices and pumping energy requirements from the California Energy Commission to estimate the marginal cost of groundwater pumping. Groundwater provides an important substitute for surface water and generates substantial spatial variation in the value of additional surface water to agricultural users. Online Appendix Section A.3 describes the construction of these data.

Urban water use. I use operations data reported by 238 residential water utilities to DWR and the American Water Works Association from 2016–2022. For each utility, I observe total water supplied, the composition of water sources, service connections, average water prices, and variable and total operating costs. I combine these data with Census income and household lot size to estimate urban water demand and the marginal value of surface water.

Hydrological balance and return flows. The DWR Water Balance reports annual agricultural, urban, and environmental water use and decomposes supply into water rights, project water, groundwater, and return flows. Environmental uses include instream-flow requirements, managed wetlands, wild and scenic rivers, and required Delta outflow. These data allow me to measure both the return flows generated by each region and the dependence of downstream agricultural, urban, and environmental users on those flows.

I combine the Water Balance with the National Hydrography Dataset (NHDPlusV2) and state and federal data on canals, aqueducts, and water-district infrastructure to construct a directed hydrological network between DAUCOs. I use this network to estimate how changes in water use at one location affect water available to downstream users. This provides the bilateral return-flow relationships that determine the externalities and feasible transfer quantities in the model. Online

Appendix Section A.5 describes construction of the network and Online Appendix Figure A.1 depicts the resulting connections.

4.2 Water transfers

Transfer data. The Public Policy Institute of California (PPIC) compiles the most comprehensive available record of California water transfers from 1982–2019. Because no single agency records all transfers, PPIC combines records from the State Water Project, Central Valley Project, State Water Resources Control Board, major water districts, and other state and federal sources. For each transfer, I observe the buyer and seller, quantity, water asset, buyer and seller use, and whether the transfer crosses the Delta. I match these transactions to the agricultural, urban, and hydrological data above and use transfers from 2005–2015 for the main market analysis.

The institutional variation described in Section 3.2 determines which regulatory requirements apply to each potential transfer. Transfers of underlying water rights require rights verification; rights transfers and project exports require return-flow determination; and transfers crossing the Delta may face carriage-water requirements. Combining these characteristics with the bilateral hydrological network allows me to observe the restrictions facing each potential buyer–seller pair and estimate the associated transaction costs from observed trade.

4.3 Descriptive Patterns

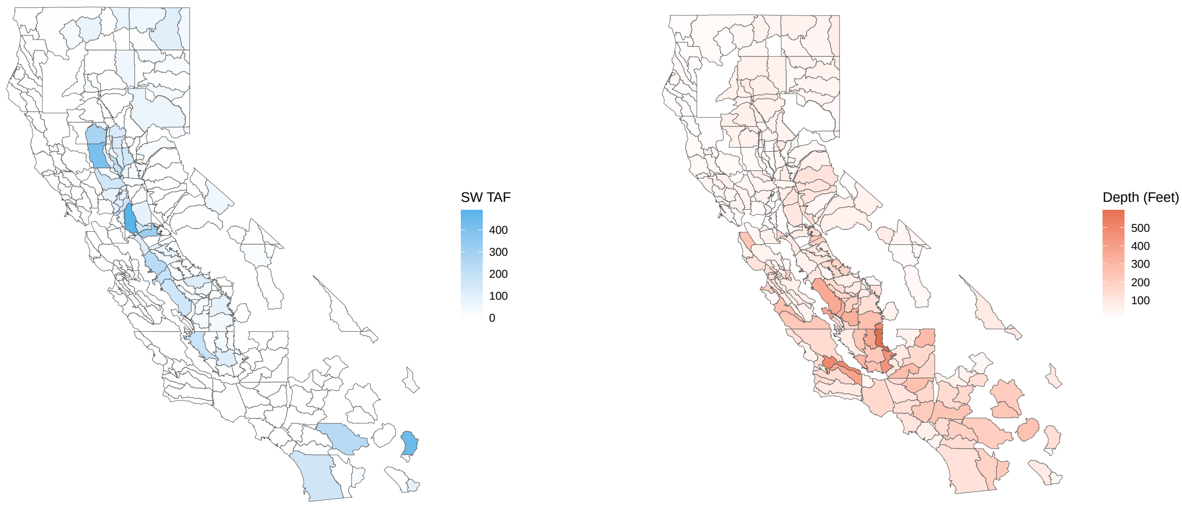
The data reveal three features of California's water allocation that motivate the model. First, the opportunity cost of surface water varies substantially across space. Agricultural users can substitute groundwater for surface water, but the cost of doing so depends on the depth from which groundwater must be pumped. Moving from normal to dry years, median DAUCO surface-water use falls by approximately 112 taf while groundwater pumping increases by 82 taf. Section 5 estimates this substitution response directly.

Figure 4 illustrates the spatial variation underlying this substitution. Surface-water use is concentrated in a different geography from the areas facing the greatest groundwater depths. Because an additional unit of surface water displaces groundwater pumping at the margin, the marginal cost of groundwater determines an agricultural user's willingness to pay for surface water. Differences in groundwater depth generate substantial spatial variation in the gains from reallocating surface water, even among agricultural users.

Second, reallocating surface water can affect users who are not party to the trade. Water diverted for irrigation is only partially consumed; the remainder returns to the hydrological system and can support downstream agricultural, urban, and environmental uses. Figure 5 shows that both the production of and dependence on these return flows are highly spatially heterogeneous. Contributions are concentrated among particular agricultural regions, while dependence is concentrated along the Sacramento–San Joaquin system and around the Delta.

This spatial heterogeneity means that otherwise similar transfers can have very different effects on third parties. A reduction in diversions by a seller whose return flows support downstream users

Figure 4: Agricultural Surface-Water Use and Groundwater Depth

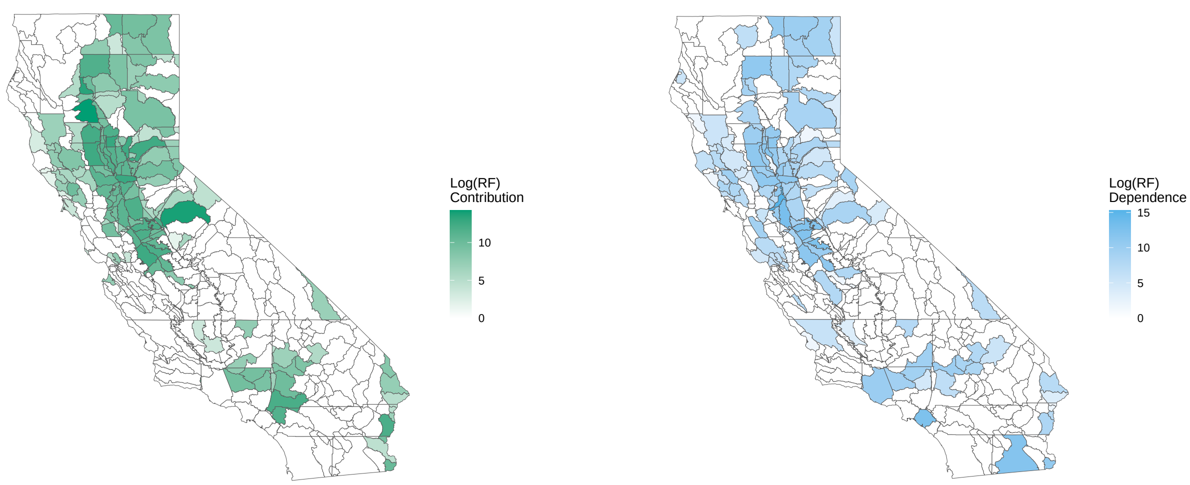


(a) Surface-water use

(b) Depth to groundwater

Notes: Both panels report DAUCO-level averages from 2005–2015. Panel (a) reports average agricultural surface-water use in thousand acre-feet (taf). Panel (b) reports average depth to groundwater in feet.

Figure 5: Return-Flow Contributions and Dependence



(a) Contributions to return flow

(b) Dependence on return flow

Notes: Panel (a) reports average return-flow contributions by DAUCO and Panel (b) reports average dependence on return flows. Quantities are shown in logs and averaged over 2005–2015.

can reduce water available elsewhere, while the same reduction by another seller may have little downstream effect. The relevant externality depends on the identity and location of the seller, creating a potential value to transaction-specific regulation. Online Appendix Section B.1 describes how I recover the network linking these observed return-flow contributions and dependencies.

Third, the observed market is both thin and highly segmented by institutional boundaries. Annual transfers generally total between 250 and 750 taf, and Figure 1(b) shows that only a small share of California surface water is traded. Most of this trade also remains within existing institutional boundaries. In a median normal year, 82% of transferred water moves between agricultural users and 69% remains within the Central Valley Project. Only 4% of volume involves the transfer of a water right, 7% involves a project export requiring return-flow determination, and 17% crosses the Delta. These institutional boundaries become more relevant when water is scarce: in a median dry year, the corresponding shares rise to 16%, 21%, and 42%, respectively. Even as scarcity increases the incentive to reallocate water, a substantial share of the trade that does occur must navigate the additional rights, return-flow, and conveyance requirements described in Section 3.

These differences provide useful variation for identifying the frictions associated with California's water-market institutions. In Section 5, I first ask whether trade is systematically lower across these institutional boundaries, conditional on the potential gains from trade and other characteristics of the buyer and seller. The structural model then uses the corresponding patterns in observed trade—together with variation in trading distance and the geographic distribution of net trade—to estimate the bilateral transaction costs associated with water rights, project exports, Delta crossings, and distance.

5 Reduced Form Analysis

I first document two patterns that motivate the structural model. Agricultural users respond strongly to changes in surface water availability by substituting to groundwater, making groundwater an important determinant of their value for surface water. I then show that the institutional requirements described in Section 3.2 strongly predict bilateral trade, but that reduced-form trade patterns alone cannot distinguish regulatory costs from the quantity restrictions and externalities associated with these transfers.

5.1 Groundwater Substitution

Farmers can respond to surface water scarcity by pumping groundwater, fallowing land, or changing crops. The agricultural production model in Section 6.1 incorporates all three margins. I first estimate the groundwater response directly using annual variation in surface water availability:

$$GW_{it} = \alpha SW_{it} + \beta \mathbf{X}_{it} + \theta_i + \xi_t + \varepsilon_{it}, \tag{3}$$

where GW_{it} and SW_{it} are groundwater and surface water use in DAUCO i and year t. The vector $\mathbf{X}_{it}$ includes effective rainfall and groundwater depth, and θ_i and ξ_t are DAUCO and year fixed

Table 1: Agricultural Response to Surface Water Availability

	Groundwater Pumped (1)
Surface Water	-0.8484***
	(0.1035)
Effective Rain	-0.8487***
	(0.1405)
Observations	4,496
R^2	0.9298
Within R^2	0.5619
DAUCO Fixed Effects	✓
Year Fixed Effects	✓

Notes: Table reports estimates from the regression specified in Equation 3 Observations are at the DAUCO-year level and the panel includes data from 2002-2020 (excluding 2004, 2009, and 2017 which are not available). Standard errors are clustered at the DAUCO-level.

effects.

Table 1 reports the results. A one acre-foot reduction in surface water is associated with a 0.85 acre-foot increase in groundwater pumping. Effective rainfall produces a nearly identical response: an additional acre-foot of irrigation requirements satisfied by rainfall reduces groundwater pumping by 0.85 acre-feet. Groundwater is the primary short-run substitute for surface water, although substitution is incomplete. This margin is central to the agricultural production model, where the cost of groundwater pumping helps determine the marginal value of surface water.

5.2 Trade Frictions

I next examine how observed trade varies with the institutional requirements described in Section 3.2. I define a market by hydrologic region, water class, and year, where water class distinguishes water rights, State Water Project (SWP) water, and Central Valley Project (CVP) water. For each origin market, I calculate the share of its surface water endowment transferred to each destination. Let s_{odt} denote the share transferred from origin o to destination d in year t, with s_{oot} denoting water retained in the origin market. I estimate

$$\log(s_{odt}) - \log(s_{oot}) = \beta X_{odt} + \theta_{ot} + \eta_d + \varepsilon_{odt}, \tag{4}$$

where X_{odt} includes indicators for transfers of water rights, project exports, Delta crossings, buyer and seller use, and distance. The specification includes origin-market-by-year and destination fixed effects. In a second specification, I control for the estimated difference in marginal willingness-to-pay between the origin and destination.

Table 2 shows that the institutional features described above strongly predict reduced trade. Transfers of water rights, project exports, and transfers crossing the Delta are all substantially less common. Because project exports require return-flow determination but not rights verification, their coefficient provides reduced-form evidence that return-flow determination itself inhibits trade. Rights transfers, which require both, are considerably less common. Delta crossings are also associated with substantially lower trade, while geographic distance plays a comparatively small role.

Table 2: Trade Friction Regression

	$\log(s_{odt}) - \log(s_{oot})$	
	(1)	(2)
CityToAg	0.1912*	1.006***
	(0.0923)	(0.1444)
CityToCity	0.1256	0.0861
	(0.0964)	(0.0829)
AgToCity	-0.3292***	-1.058***
	(0.0264)	(0.1245)
Rights	-1.694***	-1.682***
	(0.1191)	(0.1158)
Project Exports	-0.4956***	-0.4658***
	(0.0382)	(0.0379)
Cross Delta	-0.5232***	-0.4504***
	(0.0551)	(0.0596)
Distance (100 miles)	-0.0178*	-0.0219**
	(0.0093)	(0.0087)
Marginal Gain ($1k)		1.331***
		(0.2090)
Observations	11,932	11,932
R^2	0.23363	0.28414

Notes: Table reports estimates from a regression of log trade shares relative to non-traded water on various characteristics of trade using a panel of surface water transfer data from 2005 to 2015 (excluding 2009). Each observation is an origin-destination-year. Standard errors are clustered at the origin market level. Column (1) does not include any control for potential gains from trade between markets. Columns (2) includes the average difference in willingness-to-pay between markets by using estimates from structural models described in Sections 6.1 and 6.2

Potential gains from trade are also highly predictive of observed transfers. Column (2) controls for the estimated difference in marginal willingness-to-pay between origin and destination markets. Larger gains predict substantially more trade, but the coefficients on rights transfers, project exports, and Delta crossings remain negative. Controlling for gains also makes the agricultural-to-urban coefficient substantially more negative, consistent with large potential gains between agricultural and urban users that frequently remain unrealized.

These regressions establish that both gains from trade and institutional barriers matter for observed market activity, but they cannot identify the welfare consequences of removing those barriers. A transfer requiring return-flow determination, for example, may be less likely both because determining consumptive use is costly and because the resulting adjustment restricts the quantity the buyer can receive. Similarly, a Delta crossing combines regulatory costs with carriage-water and conveyance constraints. Treating all of the associated reduction in trade as a transaction cost would attribute a welfare gain to removing restrictions that protect downstream users or the environment.

Evaluating alternative market designs requires separately measuring gains from trade, hydrological externalities and associated quantity restrictions, and the costs of completing a transaction for each potential buyer–seller pair. The structural model in the next section combines estimates of agricultural and urban willingness-to-pay with the hydrological network and institutional restrictions to recover these objects jointly.

6 Model of surface water market with transaction costs

I model agricultural and urban users' willingness-to-pay for surface water and embed these values in a bilateral model of water trade. The model maps directly into the analytical framework in Section 2: bilateral reallocation generates private gains G_j, hydrological effects generate externalities E_j, regulation restricts the feasible set of transfers X_j^p, and completing a transfer may require regulatory and other transaction costs C_j^p.

6.1 Agricultural Water Demand

Agricultural users receive an annual surface water endowment SW_{it}^e from water rights and project contracts and may buy or sell water before making production decisions. After trading, DAUCO i has SW_{it} acre-feet of surface water. Farmers allocate land across crops and fallowing and use groundwater to satisfy irrigation requirements not met by surface water.

Let s_{ikt} denote the share of land L_i allocated to crop k, aw_{ikt} its applied-water requirement per acre, and π_{ikt} non-water profit per acre. Total groundwater pumping is

$$GW_{it} = \sum_k L_i s_{ikt} aw_{ikt} - SW_{it}. \tag{5}$$

Groundwater pumping is costly because water must be lifted from the aquifer and additional pumping increases pumping depth. I model groundwater cost as

$$C_{it}(GW) = P_{it}^e \rho_i \left(H_{it} GW + \frac{\gamma_i}{2} GW^2 \right), \tag{6}$$

where P_{it}^e is the price of electricity, H_{it} is groundwater depth, ρ_i converts pumping height into electricity use, and γ_i governs the increase in pumping depth as groundwater is extracted.

Farmers choose crop shares to maximize

$$\Pi_{it}(SW) = \max_{\{s_{ikt}\}} \left\{ \sum_k L_i s_{ikt} \pi_{ikt} - C_{it} \left(\sum_k L_i s_{ikt} aw_{ikt} - SW \right) - \nu L_i \sum_k s_{ikt} \log s_{ikt} \right\}, \tag{7}$$

subject to crop shares summing to one, with fallowing included as an outside option. The final term arises from heterogeneous acre-level returns to crop choices and produces smooth adjustment in crop shares. Appendix Section A.2 derives this representation from an acre-level crop-choice problem.

The agricultural value of surface water is the maximized profit function,

$$V_{it}^{A}(SW) = \Pi_{it}(SW). \tag{8}$$

Two features of this model are particularly important. First, farmers can adjust both groundwater pumping and crop choice when surface water availability changes. Second, conditional on crop allocation, the marginal value of surface water is the avoided marginal cost of groundwater pumping. The strong groundwater response documented in Section 5 directly informs agricultural willingness-to-pay. The model extends this margin by allowing water scarcity to also change which crops are grown. Detailed derivations and the connection to related multicrop models are provided in Appendix Section A.1.

6.2 Urban Water Demand

Urban water utilities supply households and face both the cost of acquiring raw water and the costs of treatment, transportation, and distribution. I estimate aggregate utility demand as

$$\log Q_{it} = \eta P_{it} + \beta \mathbf{X}_{it} + \theta_i + \xi_t + \varepsilon_{it}, \tag{9}$$

where Q_{it} is water demand, P_{it} is the average price of water, and $\mathbf{X}_{it}$ includes rainfall, household income, lot size, and population.

Inverting and integrating this demand curve gives gross consumer surplus from supplying X acre-feet. Let ϕ_{it} denote the utility's marginal cost of treatment and distribution other than acquiring the raw water itself. The utility's value of surface water is

$$V_{it}^{U}(X) = \int_{0}^{X} \left[\frac{1}{\eta} \left(\log q - \beta \mathbf{X}_{it} - \theta_i - \xi_t \right) - \phi_{it} \right] dq. \tag{10}$$

Equations 8 and 10 provide a common value function $V_{it}(W)$ for agricultural and urban participants in the water market.

6.3 Bilateral Trade and Hydrological Externalities

Consider a potential buyer–seller pair $j = (s, b, t)$. In the notation of Section 2, the action x is the seller's reduction in diversion, which I denote by w. Before trading, the seller and buyer hold W_s and W_b units of water.

I restrict the set of potential sellers to agricultural water users, while allowing both agricultural and urban buyers. City-originating transfers are negligible in the data and are likely governed by institutional frictions different from those emphasized here. Excluding these transactions focuses the model on the regulatory and hydrological margins relevant for the observed market while substantially reducing the number of potential bilateral trading pairs.

Absent hydrological or regulatory adjustments, the private gain from reallocating w units is

$$G_j(w) = V_{st}(W_s - w) - V_{st}(W_s)$$

$$+ V_{bt}(W_b + w) - V_{bt}(W_b). \tag{11}$$

Surface water trades, however, can change water available to downstream users and environmentally sensitive flows. Let $E_j(w)$ denote the resulting external harm. This object is determined by the hydrological network and depends on the identities and locations of both trading parties.

Under policy regime p, regulators may restrict the quantity that can be delivered to the buyer. Let $\alpha_j^p \in [0, 1]$ denote the fraction of the seller's reduced diversion that the buyer may receive. The feasible set is

$$X_j^p = \left\{ w : 0 \leq w \leq \overline{w}_j, \quad \text{buyer receives } \alpha_j^p w \right\}, \tag{12}$$

where $\overline{w}_j$ incorporates the seller's available water and physical conveyance constraints. Return-flow adjustments and Delta carriage-water requirements enter through α_j^p and, when applicable, through $\overline{w}_j$.

Completing the transfer also generates per-unit regulatory and transaction costs τ_j^p, so that

$$C_j^p(w) = \tau_j^p w. \tag{13}$$

The private surplus from a feasible transfer under policy p is then

$$\begin{aligned} \widetilde{G}_j^p(w) = {} & V_{st}(W_s - w) - V_{st}(W_s) \\ & + V_{bt}(W_b + \alpha_j^p w) - V_{bt}(W_b) - C_j^p(w). \end{aligned} \tag{14}$$

The bilateral transfer is

$$w_j^p \in \arg\max_{w \in X_j^p} \widetilde{G}_j^p(w). \tag{15}$$

Social surplus additionally accounts for the consequences of the trade for third parties:

$$S_j^p(w) = \widetilde{G}_j^p(w) - E_j(w). \tag{16}$$

The distinction among E_j, X_j^p, and C_j^p is central. E_j captures the underlying hydrological externality; X_j^p captures restrictions designed to mitigate that externality; and C_j^p captures the cost of measuring, approving, and completing the transaction. Observed trade can be low because any one of these objects is important.

The California institutions described in Section 3.2 map naturally into this structure. Seller-specific return-flow determinations use information about consumptive use to choose α_j^p so as to protect downstream supply, while the process of making that determination contributes to C_j^p. Delta carriage-water requirements similarly reduce delivered water through α_j^p, while regulatory review and other crossing costs enter C_j^p. Rights verification primarily affects C_j^p, while conveyance infrastructure affects the feasible set X_j^p.

This formulation also makes the policy counterfactuals transparent. Rights reforms reduce components of C_j^p. Return-flow reforms change both the cost of determining the adjustment and the rule governing α_j^p. Delta conveyance reforms relax physical restrictions on X_j^p and reduce carriage-water losses. The welfare consequences of these reforms depend on how gains from trade, externalities, feasible-transfer restrictions, and transaction costs are jointly distributed across potential buyer–seller pairs.

7 Estimation

I estimate the model in three steps. First, I estimate the agricultural parameters that determine the value function $V_{it}^{A}(SW)$ in Equation 8. Second, I estimate urban demand and production costs to recover $V_{it}^{U}(X)$ in Equation 10. Finally, I combine these value functions with the hydrological and regulatory restrictions described in Section 6.3 and estimate the transaction-cost parameters in $C_{j}^{p}(w)$ by simulated method of moments. The agricultural and urban models use exogenous variation in surface water availability for identification, while transaction costs are identified by matching observed patterns of bilateral trade.

7.1 Agricultural Parameters

I do not observe individual farmers and instead treat each DAUCO as decision maker i.[12] I observe land L_i, crop shares s_{ikt}, applied-water requirements aw_{ikt}, electricity prices P_{it}^{e}, groundwater depth H_{it}, surface water SW_{it}, and groundwater pumping GW_{it}. The parameters to recover are the response of groundwater depth to pumping γ_i, pumping efficiency ρ_i, crop-specific non-water profits π_{ikt}, and the scale of heterogeneous acre-level returns ν.

Groundwater pumping costs. I assume the endogenous effect of pumping on depth, $\gamma_i = \gamma/\text{BasinSurfaceArea}_i$, is inversely related to the groundwater basin surface area and scaled by parameter γ which is common across DAUCO. I choose γ so the groundwater pumping volume weighted average γ_i is equal the endogenous depth parameter in Timmins (2002): $\overline{\gamma} = 6.35 \times 10^{-4}$.

$$\hat{\gamma} = \arg\min_{\gamma} \left(\overline{\gamma} - \frac{\sum_{it} GW_{it}\gamma_i(\gamma)}{\sum_{it} GW_{it}}\right)^2 \tag{17}$$

I estimate pumping efficiency $\rho_i = \rho_r$ at the hydrologic region level by matching total energy used to pump groundwater E_{rt} in year t and hydrologic region r from 2005-2015.

$$\hat{\rho}_r = \arg\min_{\rho_r} \sum_{h} \left(E_{rt} - \rho_r \sum_{i\in r}\left(H_{it}GW_{it} + \frac{\gamma_i}{2}GW_{it}^2\right)\right)^2 \tag{18}$$

Crop choice. Given these estimated pumping parameters, the marginal cost of groundwater is

$$MC_{it}^{GW} = P_{it}^{e}\hat{\rho}_{r(i)}\left(H_{it} + \hat{\gamma}_i GW_{it}\right), \tag{19}$$

[12] Under the assumption that farmers within a DAUCO share non-water profit parameters π_{ikt}, accurately anticipate the pumping of other farmers, and do not strategically time groundwater extraction, the aggregate crop-choice problem is equivalent to many farmers making locally optimal crop choices.

Table 3: Acre-level Shock Parameter Estimation

	$\ln s_{ikt} - \ln s_{iot}$ (1)	Γ_{ikt} (2)
Γ_{ikt}	-0.0080***	
	(0.0027)	
Surface Water (taf)		-0.4222***
		(0.0542)
Observations	53,390	53,390
F-test (1st stage), Gamma		10,667.6
R^2	0.82459	0.80148
DAUCO × Crop FEs	✓	✓

Notes: Table reports results from a regression of the log difference of crop shares on marginal groundwater cost (marginal to crop share) when instrumenting for cost with surface water supply. The regression is at the DAUCO-crop-year level. The inverse of the coefficient on Γ_{ikt} in column (1) is the estimated parameter $\hat{\nu} = 124.33$. The second column reports the first stage where surface water resources are highly negatively correlated with groundwater cost. There are DAUCO-crop fixed effects and standard errors are clustered at the DAUCO level.

which enables estimation of the scale of acre-level crop-choice heterogeneity, ν, and non-water crop profits π_{ikt}. The first-order condition from the agricultural problem in Equation 7 relative to the fallowing option $k = 0$, is

$$\nu \left(\ln s_{ikt} - \ln s_{i0t}\right) = \pi_{ikt} - a w_{ikt} MC_{it}^{GW}. \tag{20}$$

Define the groundwater cost associated with irrigating an acre of crop k as $\Gamma_{ikt} \equiv a w_{ikt} MC_{it}^{GW}$. Dividing Equation 20 by ν gives the estimating equation

$$\ln s_{ikt} - \ln s_{i0t} = \delta_{ik} - \frac{1}{\nu}\Gamma_{ikt} + \varepsilon_{ikt}, \tag{21}$$

where DAUCO-by-crop fixed effects δ_{ik} absorb average non-water profitability, π_{ik}/ν.

Groundwater costs are endogenous because groundwater pumping responds to farmers' production choices. I instrument for Γ_{ikt} using annual surface water availability. Conditional on DAUCO-by-crop fixed effects, the identifying assumption is that within-DAUCO variation in surface water availability affects crop choice through the cost of replacing surface water with groundwater and is uncorrelated with shocks to non-water crop profitability. This is the same source of variation underlying the groundwater substitution results in Section 5.1.

Table 3 reports the IV estimate and first stage. Surface water availability strongly reduces the marginal groundwater cost of crop production, with a strong first-stage F-statistic. Inverting The estimated coefficient on Γ_{ikt} identifies our estimate of $\hat{\nu} = 124.33$. This IV estimator is equivalent to recovering non-water profits for candidate values of ν and imposing that within-DAUCO-crop variation in those profits is orthogonal to surface water availability.

Table 4: Agricultural Model Parameters and Estimates

	Mean	p10	p50	p90
Crop Non-water Profit π_{ikt}, \$/af				
Alfalfa	58.3	9.71	38.8	119
Almonds/Pistachios	49.6	11.4	41.5	101
Citrus/Subtropical	86.1	16	55.2	187
Corn	35	5.43	30.2	67.6
Cotton	47.8	10.9	30.8	109
Cucurbits	61.4	4.93	40	129
Dry Beans	26.9	3.37	21.2	60.8
Fresh Tomato	36.2	2.91	27	89.7
Grain	54.2	12.8	40.1	109
Onion/Garlic	68	13.7	68.9	121
Other Deciduous	32.2	9.03	27.4	57
Other Field	45.9	7.34	35	96.8
Pasture	43.9	9.47	28.6	98.1
Potato	92.3	16.1	90.2	171
Processing Tomato	36	4.34	26.6	92
Rice	19.3	4.61	17.1	38.9
Safflower	40.8	3	26.9	115
Truck Crops	71.8	14.8	45.6	155
Vineyard	51.3	14.9	39.4	103
Other Agr. Parameters				
Electricity Price, \$/kWh	0.118	0.0998	0.118	0.147
Pumping Efficiency ρ_i, kWh/af/ft	2.09	1.49	2.05	2.76
Endogenous Depth γ_i, ft/af	6.4e-04	1.2e-04	2.7e-04	15.4e-04
GW Depth, ft	95.2	14	66.6	218
Marginal WTP, \$	54.1	9.06	32.7	104
Scale of Acre-level Shocks, ν	124.33			

Notes: Table summarizes estimates for the agricultural model on the panel of DAUCO-level data from 2005-2015. For each crop, I report summary statistics about the estimated non-water profit parameters. I report the mean, 10th, median, and 90th percentiles of non-water profit per acre-foot within crop and across DAUCO-years. At the bottom of the table, I report similar summary statistics for the groundwater cost parameters and the estimated scale of acre-level shocks.

Finally, given $\hat{\nu}$, I invert Equation 20 to recover DAUCO-crop-year non-water profits:

$$\hat{\pi}_{ikt} = \hat{\nu}\left(\ln s_{ikt} - \ln s_{i0t}\right) + \Gamma_{ikt}. \tag{22}$$

Together, the estimated non-water profits and groundwater cost parameters determine farmers' crop choices and the agricultural value function $V_{it}^{A}(SW)$ used in the trading model. In Table 4 I report summary statistics of agricultural parameters. For each crop, I report the mean, median, 10th, and 90th percentiles of non-water crop profit per acre-foot, π_{ikt}/aw_{ikt}.[13]

The four crop categories with the highest average non-water profit per acre-foot are potato, citrus/subtropical, truck crops, and cucurbits. The lowest profit crops include rice, dry beans, other

[13] In Online Appendix Table B.1 I report the same statistics for applied water needs per acre, aw_{ikt}.

deciduous, and corn. The estimates largely correspond with priors that specialty fruits and nuts are highly profitable and cash crops are relatively less valuable. In Online Appendix Figure B.1 I show the highest profit crop per acre-foot for each DAUCO.

I also report statistics for the other groundwater parameters along with final estimates of the marginal willingness-to-pay for surface water. Electricity prices from 2005-2015 for agricultural consumers average about $0.12 per kWh. Pumping efficiency estimates vary between 1.4 and 3.8 kWh/af/ft. [14] On average, farmers increase the depth to groundwater by one foot for every 22 thousand acre-feet pumped, but this varies substantially across DAUCOs depending on the size of the basin. The average marginal willingness-to-pay for water is $54.10 per acre-foot.[15]

7.2 Estimation of urban demand and production cost

I estimate the demand specified in Equation (9) using audit data of all California water utilities from 2016-2022. To address price-quantity endogeneity I instrument for price with the quantity of water supply that is guaranteed to the utility that year according to their own property rights.

California utilities obtain water through a combination of their own rights and contracts and purchases from wholesalers. Utilities with their own secure right are guaranteed a level of supply whereas utilities without their own water resources are subject to wholesaler prices and bargaining. For relevance, utilities with more secure water supply will have lower prices for consumers. Exclusion is satisfied by this instrument because within utility variation in owned surface water right volume is determined by exogenous hydrological conditions, like annual snowpack, which are unlikely to be correlated with utility-level shocks to demand.[16]

In Table 5 I report the results from this estimation. Columns (1)-(3) report estimates from the instrumental variables specification, ordinary least squares, and the first-stage, respectively. Without instrumenting, the OLS elasticity underestimates the magnitude of the demand elasticity. Using utility's owned supply as an instrument, I estimate that urban water demand is inelastic. Evaluated at average prices, my estimate of the demand elasticity with respect to average unit price is 0.18. Leveraging my preferred spec in column (1) to back out surplus values for surface water, I subtract reported production costs as in Equation 6.2 to compute residential willingness-to-pay for surface water on the open market.

[14] In Online Appendix Figure B.3 I map the geographic variation in pumping efficiency.

[15] Burlig et. al (2024) construct a model of groundwater demand using microdata on pumping and electricity data and estimate average marginal groundwater cost at $47.37/af.

[16] I control for local rain in estimation, which may effect demand but not supply, which is determined by snowpack.

Table 5: Urban Demand Estimation

	LogQuantity		Price (\$100)
	IV	OLS	First-Stage
Price (\$100)	-0.0094**	-0.0023***	
	(0.0043)	(0.0008)	
LogRain	-0.0018	-0.0032	0.1885
	(0.0253)	(0.0151)	(2.140)
LogHouseholds	0.7905***	0.7952***	-0.2895
	(0.0808)	(0.0819)	(1.133)
LogVolOwn			-1.024***
			(0.2200)
Observations	1,998	1,998	1,998
F-test (1st stage), Price			46.332
R^2	0.99875	0.99900	0.95654
Within R^2	0.58473	0.66782	0.02788

Notes: Table reports estimates from the urban demand regression of logged utility supply quantity on price and various covariates specified in Equation 9 Fixed effects are included at the Year × Hydrological Region and utility level. Standard errors are clustered at the Year × Hydrological Region level. The regression is estimated on an unbalanced panel of data from 2016-2022 with 362 utilities. The regression is weighted by service connections.

In Figure 6 I depict the distribution of estimated marginal willingness-to-pay across DAUCOs and urban utilities. Clearly there are large gains to be made from trade between farmers and cities with median gains of \$524/af. To rationalize limited market activity despite this evidence, there are likely large transaction costs.

7.3 Transaction Costs

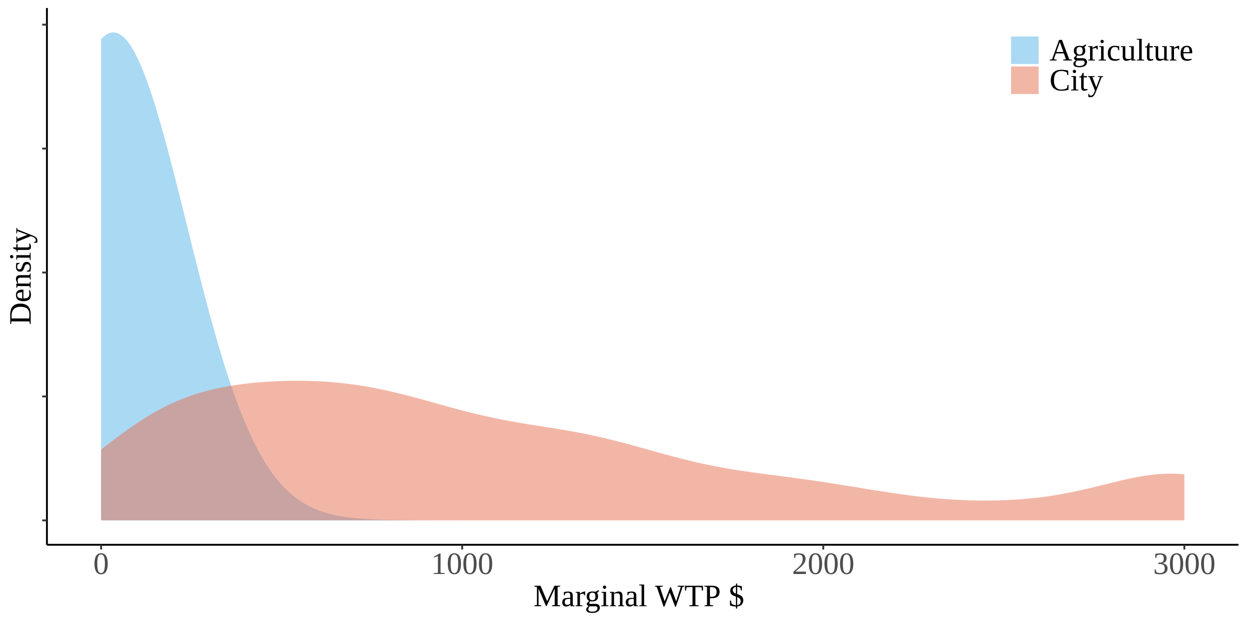
I next estimate the transaction costs $C_j^p(w)$ governing bilateral trade. For buyer–seller pair $j = (s, b, t)$ under the status quo policy regime, I assume these costs are linear in the quantity transferred, $C_j^p(w) = \tau_{sbt} w$. I parameterize the per-acre-foot transaction cost as

$$\begin{aligned} \tau_{sbt} = \mu_{u(b)} + \beta_R \text{Right}_{sbt} + \beta_P \text{ProjectExport}_{sbt} + \beta_D \text{CrossDelta}_{sbt} \\ + \beta_d \text{Distance}_{sb} + \psi_{r(s)} - \psi_{r(b)} + \sigma_\tau \varepsilon_{sbt}, \end{aligned} \tag{23}$$

where $u(b)$ denotes whether buyer b is agricultural or urban, $\mu_{u(b)}$ are buyer-use fixed effects, and ε_{sbt} is an i.i.d. standard normal shock observed by trading agents but not by the econometrician.

The coefficients β_R, β_P, and β_D capture incremental frictions associated with transferring a water right, exporting project water, and crossing the Delta. Importantly, these parameters do not capture the quantity restrictions imposed to protect against hydrological externalities. As in the framework of Section 2, those restrictions enter separately through α_j^p and the feasible set

Figure 6: Estimated Marginal WTP: Agriculture vs. Urban



Notes: Figure depicts the distribution of marginal willingness-to-pay per acre-foot at pre-trade surface water endowments for agricultural DAUCOs and urban utilities. The empirical distribution shown is estimated on California data from 2012-2015 using the procedures described in Sections 6.1 and 6.2.

X_j^p. The coefficients in Equation (23) measure additional costs of completing these transactions *conditional on* the applicable restrictions on transferable quantities. This distinction will allow the counterfactuals to separately vary the cost of administering a regulation and the protective constraint that regulation imposes.

The remaining parameters absorb other sources of heterogeneity in bilateral trade. The buyer-use fixed effects $\mu_{u(b)}$ capture residual differences in trading propensity between agriculture-to-agriculture and agriculture-to-city transactions and are not interpreted as particular transaction costs. They may reflect search, bargaining, infrastructure, political constraints, or other unmodeled barriers to trade. The coefficient β_d captures frictions that increase with geographic distance, while hydrologic-region terms ψ_r allow for persistent differences in net trading behavior across regions. Finally, σ_τ governs residual pair-specific heterogeneity in trade frictions.

I estimate these parameters by simulated method of moments using water-market outcomes from 2012–2015. For a candidate parameter vector

$$\theta_\tau = (\{\mu_u\}, \beta_R, \beta_P, \beta_D, \beta_d, \{\psi_r\}, \sigma_\tau)\,. \tag{24}$$

and a draw of ε_{sbt}, I simulate the bilateral market described in Section 6.3. Potential buyers and sellers are randomly paired and execute their jointly surplus-maximizing transfer in Equation 15. Because previous trades change agents' water holdings and hence their marginal values, outcomes depend on the order in which trading opportunities arrive. I therefore average simulated moments over random trading orders.

I estimate these parameters by simulated method of moments using water-market outcomes from 2012–2015. The estimation sample and simulated market include agricultural sellers and agricultural or urban buyers. Trade volumes for agriculture-to-agriculture and agriculture-to-city transactions discipline the buyer-use fixed effects. Trade involving water rights, project exports, and Delta crossings identifies β_R, β_P, and β_D, while the quantity-weighted distance between trading partners identifies β_d. Net trade by hydrologic region identifies ψ_r, and residual variation in bilateral trade identifies σ_τ. Table 9 reports the full set of observed and simulated moments.

For each candidate parameter vector, I draw $R = 100$ vectors of transaction-cost shocks and calculate the average simulated moment vector,

$$\overline{M}(\theta_\tau) = \frac{1}{R}\sum_{r=1}^{R} \widehat{M}\left(\theta_\tau, \varepsilon^r\right), \qquad \bar{e}(\theta_\tau) = \frac{\overline{M}(\theta_\tau) - M}{M}, \tag{25}$$

where division in the second expression is element-by-element. I estimate θ_τ by

$$\widehat{\theta}_\tau = \arg\min_{\theta_\tau} \bar{e}(\theta_\tau)' W \bar{e}(\theta_\tau), \tag{26}$$

where W is the inverse variance–covariance matrix of the moments, obtained using a two-step procedure as in Hansen & West (2002).

7.4 Discussion of Trading Model

The trading model makes two substantive sets of assumptions, concerning trading conduct and the interpretation of the estimated trade frictions.

First, I approximate the decentralized water market as a sequence of bilateral trades among agricultural sellers and agricultural or urban buyers. I exclude city-originating transfers, which are negligible in the data and likely face additional institutional frictions outside the focus of the model. When a buyer and seller meet, they choose the transfer that maximizes their joint surplus net of transaction costs, taking future trading opportunities as given. This captures two salient features of the setting: transfers are predominantly bilateral, and the costs and constraints facing a trade depend on the identities and locations of the two parties. The approximation abstracts from strategic decisions to withhold water in anticipation of more attractive future trading partners.

Because trades change agents' water holdings and hence their marginal values, the resulting allocation can depend on the order of bilateral meetings. I do not take a particular ordering as an equilibrium selection mechanism. Instead, I randomize the order of trading opportunities and integrate over this variation in estimation and counterfactuals. The model should be interpreted as describing average outcomes generated by decentralized bilateral trade rather than a unique equilibrium allocation.

Second, the estimated coefficients in Equation (23) should be interpreted as reduced-form measures of incremental trading frictions, not as engineering estimates of individual administrative costs. For example, the project-export coefficient captures the incremental friction associated with transactions requiring return-flow determination, but may also incorporate correlated costs of project approval or coordination. Similarly, the water-right coefficient can reflect both the requirements particular to establishing and transferring a right and other frictions systematically associated with those transactions. Limited policy variation prevents these components from being separately identified.

This limitation motivates both the parameterization and the interpretation of the counterfactuals. Broad differences between agricultural and urban buyers are absorbed by the buyer-use fixed effects rather than assigned to particular institutions, while the institutional coefficients isolate incremental differences associated with observable transfer requirements. Most importantly, hydrological protections themselves are modeled separately from these estimated frictions. I can distinguish removing an estimated cost associated with administering a rule from removing the underlying restriction on trade. The counterfactuals should be interpreted as varying these estimated institutional margins, rather than as claiming that each coefficient identifies a single literal administrative expense.

8 Results

I first report the estimated institutional trade frictions and describe market outcomes under the estimated baseline model. I then use the model to evaluate reforms to rights administration, return-flow regulation, and Delta conveyance. Finally, I study the design of return-flow regulation more directly, comparing the current transaction-specific approach with simpler rules that require less information about individual sellers.

8.1 Parameter Estimates and Baseline Market Outcomes

Institutional trade frictions. Table 6 reports the estimated transaction cost parameters associated with the institutional characteristics of a transfer. The estimates are expressed in dollars per acre-foot transferred.

The estimates reveal substantial differences across the institutional requirements governing trade. Project exports face an estimated additional friction of \$29.11 per acre-foot. Because project exports require a determination of the seller's consumptive use but do not require verification of an underlying water right, I interpret this estimate as the model's measure of the incremental cost associated with return-flow determination and related approval requirements.

Transfers of water rights face an estimated friction of \$54.42 per acre-foot. Rights transfers require both return-flow determination and verification of the seller's underlying right and transferable quantity. The difference between the rights-transfer and project-export estimates suggests that establishing and transferring the underlying right imposes an additional cost of roughly \$25 per acre-foot beyond the costs associated with return-flow determination.

The residual friction associated with crossing the Delta is \$10.79 per acre-foot, while an additional 100 miles of distance increases transaction costs by approximately \$35.54 per acre-foot.

Table 6: Estimated Institutional Trade Frictions

	Estimated Cost ($/AF)
Water-right transfer	54.42
Project export	29.11
Delta crossing	10.79
Distance (100 miles)	35.54

Notes: The table reports estimates of the institutional transaction cost parameters in Equation 23. Water-right transfers require rights verification and return-flow determination. Project exports require return-flow determination but not rights verification. Delta crossings may require additional regulatory approval and coordination. The model separately accounts for restrictions on transferable quantities, including return-flow adjustments and Delta carriage-water requirements, so these coefficients capture incremental frictions associated with completing the corresponding transactions. The specification additionally includes seller-use-by-buyer-use and hydrologic-region fixed effects, reported in Appendix Table 9.

Importantly, the Delta coefficient does not capture the water that must be left in the system as carriage water: that restriction enters separately through the quantity delivered to the buyer. The estimate instead captures the residual cost associated with executing a Delta-crossing transfer conditional on this physical and regulatory restriction.

The model also estimates seller-use-by-buyer-use fixed effects that absorb residual differences in trading frictions across agricultural and urban trading pairs. Some of these residual frictions are large, particularly for agricultural-to-urban transfers. I do not assign these fixed effects a structural interpretation: they may reflect search and bargaining costs, political constraints, infrastructure, institutional differences, or other unmodeled barriers to trade. Appendix Table 9 reports these estimates together with the hydrologic-region fixed effects. Their magnitude is important for interpreting the counterfactuals below: reforming the particular institutional frictions that I identify does not eliminate the many other barriers that continue to inhibit water trade.

Baseline market outcomes. Before considering reforms, Table 7 summarizes market outcomes generated by the estimated model. I report results separately for dry, normal, and wet years because scarcity substantially changes both the volume and value of trade.

Table 7: Baseline Water Market Outcomes

	Dry	Normal	Wet
Trade volume (TAF)	357.0	286.0	147.0
Agricultural gains from trade ($ million)	80.5	64.3	33.9
Urban gains from trade ($ million)	118.9	115.4	9.6
Transaction costs ($ million)	137.0	117.5	39.5
Groundwater pumping (MAF)	23.6	23.6	23.2

Notes: The table reports average simulated market outcomes under the estimated status-quo model, separately by hydrological year type. Trade volume is measured in thousand acre-feet (TAF), and monetary outcomes are in millions of dollars.

The baseline model generates a relatively thin market despite substantial dispersion in willingness-to-pay. In dry years, approximately 357 TAF are traded. These transfers generate $80.5 million in gains to agricultural water users and $118.9 million in gains to urban water users, against $137.0 million in transaction costs. Trade falls to 286 TAF in normal years and 147 TAF in wet years. The value of trade falls particularly sharply in wet years, when agricultural and urban gains from trade total only $43.5 million.

This variation motivates my focus on dry years in the main counterfactual analysis. Water-market reforms are most valuable precisely when surface water is scarce and marginal values are most dispersed.

8.2 Counterfactual Market Reforms

I next use the estimated model to evaluate reforms to the institutional and physical constraints governing surface water trade. The analytical framework in Section 2 distinguishes between the restrictions used to mitigate the externalities created by trade and the costs of implementing those restrictions. This distinction is important for interpreting the counterfactuals. Removing a regulatory cost can facilitate trade without weakening third-party protections, while removing the underlying restriction on transferable quantities may instead expose downstream users or the environment to additional harm.

I consider reforms to three institutional margins. First, I eliminate the estimated cost of determining seller-specific return flows while retaining the resulting consumptive-use adjustment. In the notation of Section 2, this reduces C_j^p while leaving the transaction-specific restriction on X_j^p unchanged. Second, I consider improved Delta conveyance, which relaxes restrictions on moving water across the Delta. Third, I eliminate the estimated cost associated with verifying and transferring water rights. I consider these reforms both individually and in combination because the value of relaxing one constraint may depend on which other constraints continue to bind.

Table 8 reports changes relative to the baseline for dry years. I focus on dry years because this is when water scarcity creates the largest potential gains from reallocation.

Eliminating the administrative cost of seller-specific return-flow determination increases dry-year trade by 115 TAF, or about one-third relative to baseline trade. The additional transfers generate $27.8 million in agricultural gains and $0.4 million in urban gains, while transaction costs incurred on the expanded set of trades rise by $25.4 million. Return-flow determination meaningfully reduces the volume of trade, but eliminating this cost alone produces relatively small net gains because other trading frictions remain.

Delta conveyance reform, which eliminates both the additional cost of crossing the Delta and the associated carriage-water constraint, has a larger effect. Trade increases by 175 TAF, generating $50.7 million in additional agricultural gains and $4.6 million in urban gains. The reforms are strongly complementary. Combining Delta reform with costless return-flow determination increases trade by 357 TAF—approximately doubling baseline dry-year trade—and generates $101.8 million in additional gains to water users.

Table 8: Counterfactual Results Relative to Baseline: Dry Years

Counterfactual	Δ Trade (TAF)	Δ Ag. Gains ($M)	Δ Urban Gains ($M)	Δ Costs ($M)	Δ Pumping (%)
No RF determination cost	115	27.8	0.4	25.4	-0.09
Delta conveyance reform	175	50.7	4.6	45.2	0.06
Delta conveyance reform + no RF cost	357	96.7	5.1	87.4	-0.18
Delta conveyance and rights reform	278	78.3	5	70.7	-0.06
Delta conveyance and rights reform + no RF cost	644	163.3	5.4	147.5	-0.54

Notes: Entries report changes relative to the estimated baseline market in dry years. "No return-flow determination cost" eliminates the estimated administrative friction associated with seller-specific consumptive-use determination while retaining seller-specific return-flow adjustments. "Delta conveyance reform" "Delta conveyance reform" eliminates both the estimated incremental cost associated with Delta-crossing transfers and the carriage-water requirement that restricts the quantity delivered to buyers south of the Delta. "Rights reform" eliminates the estimated incremental friction associated with verifying and transferring water rights while retaining applicable protections for downstream users.

Rights reform is similarly more valuable when combined with improved Delta conveyance. Jointly reforming Delta conveyance and the costs associated with transferring water rights increases trade by 278 TAF and generates $78.3 million in additional agricultural gains and $5.0 million in urban gains. When these reforms are also combined with costless return-flow determination, trade rises by 644 TAF relative to baseline, bringing total dry-year trade to approximately 1.0 million acre-feet. Agricultural gains rise by $163.3 million and urban gains by $5.4 million. Groundwater pumping falls by approximately 0.13 MAF.

These results reveal substantial complementarity across institutional reforms. For example, Delta reform and costless return-flow determination individually increase trade by 175 and 115 TAF, respectively, while implementing them together increases trade by 357 TAF. Reducing one barrier creates more value when other constraints no longer prevent the same buyer–seller pair from trading. At the same time, substantial residual trading frictions remain. The counterfactuals should be interpreted as targeted reforms to the institutions studied here rather than as eliminating every barrier to California water trade. At the same time, the increase in transaction costs as the market expands shows why these counterfactuals should not be interpreted as eliminating all barriers to trade. Large residual use-to-use frictions remain, as reported in Appendix Table 9.

8.3 Market Reform and Regulatory Precision

The preceding counterfactuals maintain California's existing approach to return-flow externalities: regulators determine a seller's consumptive use and limit the quantity delivered to the buyer accordingly. This approach has an important advantage. Because externalities vary across trades, transaction-specific information allows regulators to distinguish transfers with small downstream effects from those that would substantially reduce water available elsewhere. But obtaining and implementing this information is itself costly. I now ask whether simpler regulations that dispense with transaction-specific information can perform better, and how the answer depends on the other frictions in the market.

This exercise maps directly into the regulatory tradeoff in Section 2. With costless information, a regulator can tailor a performance standard to each transaction's externality. When information is costly, however, the regulator can instead use a coarse rule that applies uniformly across transactions. I consider two such alternatives: a uniform tax and a uniform performance standard.

The cost and value of transaction-specific information. The estimated magnitudes make the tradeoff between information and coarse regulation particularly stark. The average marginal return-flow externality in the model is \$35.20 per acre-foot. By comparison, the estimated incremental cost associated with determining and implementing a seller-specific return-flow adjustment is \$29.11 per acre-foot. The cost of acquiring the information needed to directly mitigate heterogeneous return-flow externalities is actually smaller than the average externality being regulated.

This comparison makes it far from obvious that replacing the existing system with a simple tax would reduce the costs of regulation. Paying \$29.11 per acre-foot allows the regulator to determine which transfers generate large downstream effects and to adjust transferable quantities accordingly. A uniform tax avoids this information cost, but must instead price transactions without knowing their individual externalities. A tax based on the average externality overprices relatively benign transfers and underprices transfers with large return-flow effects.

The preceding counterfactuals quantify the cost of information directly. Figure 7 reports costly seller-specific regulation with squares and the same regulation with costless information with asterisks. Eliminating the information cost can generate substantial additional surplus, particularly after other barriers to trade have been removed. Costless transaction-specific information is not, however, an available policy. The relevant question is whether a regulator can economize on information without giving up too much of the protection that seller-specific regulation provides.

Coarse alternatives: uniform taxes and performance standards. I consider two regulations that require no seller-specific return-flow information. The first replaces the return-flow adjustment with a uniform \$35.20 per-acre-foot tax, equal to the average marginal return-flow externality. Unlike a transaction-specific Pigouvian tax, this policy does not vary with the externality created by the particular seller.

The second is a *uniform performance standard*. Rather than determine each seller's return flows, the regulator permits every buyer to divert a common fraction α of the seller's reduction in diversions. For example, $\alpha = 0.7$ permits the buyer to divert 7 acre-feet when the seller reduces diversions by 10 acre-feet, leaving the remaining 3 acre-feet in the hydrological system. Varying α traces the curves in Figure 7.

Among these standards, I focus on the least restrictive rule that preserves the no-harm protection underlying California water law. Specifically, I choose the largest α that causes neither a loss of environmental water nor a reduction in water available to any downstream water user. This policy does not attempt to reproduce each seller's return-flow effect. Instead, it asks how permissive a common rule can be while maintaining the downstream protections that motivate the existing seller-specific review.

Figure 7 compares these regulations under three market environments: the estimated baseline, a market without Delta frictions, and a market without either Delta frictions or the costs associated with transferring water rights. Squares report the existing costly seller-specific regulation, asterisks make seller-specific information costless, triangles report the no-harm uniform performance standard, and crosses report the uniform mean-externality tax.

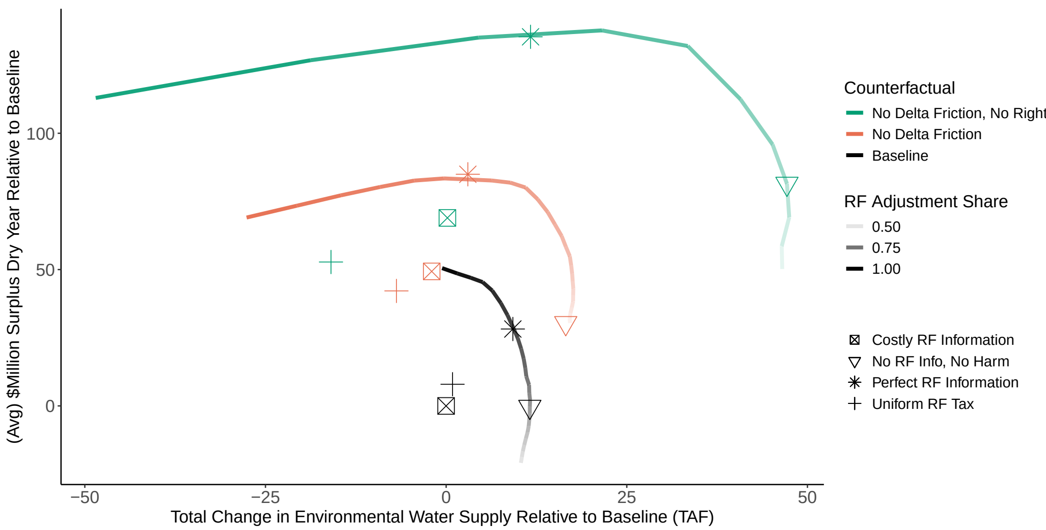


Figure 7: Return-Flow Regulation under Alternative Market Institutions

Notes: The horizontal axis reports the change in water remaining in the hydrological system relative to the estimated baseline, and the vertical axis reports the change in dry-year surplus relative to the estimated baseline. Curves report outcomes under uniform return-flow adjustments α, where buyers may divert fraction α of the seller's reduction in diversion. Squares denote costly seller-specific return-flow regulation, asterisks denote costless seller-specific regulation, triangles denote the largest uniform α satisfying the no-harm criterion, and crosses denote a uniform $35.20 per-acre-foot tax equal to the average marginal return-flow externality. The no-harm criterion requires that the policy cause neither a loss of environmental water nor a reduction in water available to any downstream water user.

Existing return-flow regulation performs well in the current market. Under current market institutions, there is little evidence that simplifying return-flow regulation should be the first margin of reform. The least restrictive uniform performance standard satisfying the no-harm criterion is $\alpha = 0.68$ and generates approximately the same surplus as the existing seller-specific regime. The uniform mean-externality tax generates somewhat more surplus, approximately $7.9 million, but does so without guaranteeing protection of individual downstream users. By comparison, making the existing seller-specific information costless would increase surplus by approximately $28 million.

These results put the estimated $29.11 information cost in perspective. Although seller-specific review is expensive, the information it produces is valuable: it permits regulators to relax restrictions on relatively benign transfers while protecting downstream users from transfers with larger externalities. Given the other frictions currently limiting the market, neither coarse alternative offers a compelling improvement over paying for this information. In this sense, California's existing return-flow regulation performs relatively well despite its administrative cost.

The case for simpler regulation emerges after broader market reform. The comparison changes as other barriers to trade are removed. Following Delta reform, costly seller-specific regulation generates \$49.3 million in additional surplus while reducing environmental water by 2.0 TAF. The uniform tax generates \$42.2 million while reducing environmental water by 6.9 TAF. The no-harm uniform performance standard is more protective but also more restrictive: $\alpha = 0.50$ generates \$30.4 million in additional surplus. After Delta reform alone, the existing seller-specific approach continues to perform well.

Following both Delta and water-right reform, however, a simpler uniform performance standard becomes substantially more attractive. Costly seller-specific regulation generates \$69.0 million in additional surplus and leaves environmental water approximately unchanged. The no-harm uniform standard, with $\alpha = 0.65$, generates \$81.5 million while increasing environmental water by 47.2 TAF. It therefore generates more surplus while preserving the downstream no-harm protection, despite using no transaction-specific return-flow information.

The uniform tax performs much worse in this more liberalized market. It generates only \$52.8 million in additional surplus and reduces environmental water by 15.9 TAF. This divergence reflects two forces. Like the tax, the uniform performance standard avoids the cost of seller-specific return-flow determination. But unlike the tax, it directly restricts the quantity of water that can be transferred in order to protect downstream flows. As rights and conveyance reforms permit substantially more trade, the consequences of transactions with large return-flow externalities become increasingly important. A tax based on the *average* externality does not prevent these transactions and therefore permits increasingly large downstream harms. The no-harm performance standard avoids these harms without restoring the cost of transaction-specific review.

Implications for regulatory design. These results imply that the appropriate way to regulate trade externalities depends on the broader architecture of the market. Under existing institutions, the costs of acquiring seller-specific information appear to be worth paying. The average externality being regulated is larger than the estimated cost of determining and implementing the corresponding seller-specific adjustment, and coarse alternatives provide little improvement without weakening downstream protections.

Nor does market liberalization imply that these protections should be relaxed. Instead, sufficiently broad reform changes the regulatory technology that can deliver them most efficiently. Once other barriers to trade are substantially reduced, a uniform performance standard can avoid the recurring cost of seller-specific information while continuing to satisfy the no-harm requirement. By contrast, a uniform tax becomes less attractive because the expansion of trade magnifies the consequences of the heterogeneous externalities that a common tax cannot target.

The policy implication is one of sequencing. Simplifying return-flow review in isolation produces little benefit: under the existing market structure, regulators appear to be purchasing useful information. The case for a simpler uniform performance standard arises only alongside substantial reforms to other barriers to trade. Regulatory simplification and market liberalization should be designed jointly, while preserving the downstream protections that motivate return-flow regulation in the first place.

9 Conclusion

This paper studies why large potential gains from water reallocation coexist with so little trade. I develop and estimate a spatial model of California's surface water market that incorporates heterogeneous water values, hydrological externalities, regulatory constraints, and bilateral trade frictions. The results show that no single barrier explains the thinness of the market: rights administration, conveyance constraints, return-flow regulation, and other trading frictions interact, so reforms that appear modest in isolation can generate much larger gains when implemented together.

At the same time, not every barrier to trade is a distortion that should be removed. California's return-flow regulation is costly because it requires information about the externality created by individual transfers, but the estimated cost of obtaining this information is smaller than the average externality being regulated. Under existing market institutions, this information appears worth acquiring. The case for simpler regulation emerges only after substantial reforms elsewhere in the market, when a uniform performance standard can avoid transaction-specific information costs while preserving downstream no-harm protections. A uniform tax performs less well because it does not directly prevent high-externality trades as market activity expands.

These results point to a broader lesson for the design of markets with heterogeneous externalities. The appearance of transaction costs should not by itself be taken as evidence that regulation is creating unnecessary friction. Some transaction costs are the price of acquiring the information needed to manage externalities, and removing them can make the market less, rather than more, efficient. In our setting, absent broader market reform, the costs of seller-specific return-flow regulation appear worth paying. More generally, whether regulatory precision is worth its cost depends on the heterogeneity of externalities, the cost of information, and the other institutions governing exchange. Market reform changes not only the gains from trade but also the regulatory problem created by that trade. The challenge is not simply to eliminate transaction costs or price the average externality, but to design markets and their regulation together.

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A Additional Details on the Agricultural Model

A.1 Smooth Crop-Share Representation

This appendix derives the crop-share condition used in the agricultural estimation. Agricultural user i has L_i acres and allocates shares s_{ikt} across crops $k \in K$, including fallowing. Crop k generates non-water profit π_{ikt} per acre and requires aw_{ikt} acre-feet of applied water per acre. Given surface-water supply SW_{it}, groundwater pumping is

$$GW_{it} = L_i \sum_k s_{ikt} aw_{ikt} - SW_{it}. \tag{27}$$

As in the main text, the agricultural user solves

$$\max_{\{s_{ikt}\}_k} \left\{ L_i \sum_k s_{ikt}\pi_{ikt} - C_{it}(GW_{it}) - \nu L_i \sum_k s_{ikt} \log s_{ikt} \right\} \tag{28}$$

subject to

$$\sum_k s_{ikt} = 1, \qquad s_{ikt} \geq 0.$$

The final term provides a smooth representation of crop adjustment and captures costs associated with concentrating acreage in a small number of crops, including crop rotation, quasi-fixed inputs, and constraints on the timing of production (Carpentier & Letort, 2014).

Let

$$MC_{it}^{GW} = P_{it}^{e}\rho_i \left(H_{it} + \gamma_i GW_{it}\right) \tag{29}$$

denote the marginal cost of groundwater pumping. The marginal groundwater cost associated with allocating an additional acre to crop k is

$$\Gamma_{ikt} \equiv aw_{ikt} MC_{it}^{GW} = aw_{ikt} P_{it}^{e}\rho_i \left(H_{it} + \gamma_i GW_{it}\right). \tag{30}$$

The first-order condition for crop k is

$$\pi_{ikt} - \Gamma_{ikt} - \nu \left(\log s_{ikt} + 1\right) - \frac{\lambda_{it}}{L_i} = 0, \tag{31}$$

where λ_{it} is the multiplier on the acreage constraint. Letting crop 0 denote fallowing, with $aw_{i0t} = 0$ and $\pi_{i0t} = 0$, subtracting the fallowing first-order condition from that for crop k gives

$$\nu \left[\log s_{ikt} - \log s_{i0t}\right] = \pi_{ikt} - \Gamma_{ikt}. \tag{32}$$

Equivalently, crop shares take the logit form

$$s_{ikt} = \frac{\exp\left\{(\pi_{ikt} - \Gamma_{ikt})/\nu\right\}}{\sum_{j\in K} \exp\left\{(\pi_{ijt} - \Gamma_{ijt})/\nu\right\}}. \tag{33}$$

Equation (32) is the condition used in the agricultural estimation in Section 4.

A.2 Acre-Level Interpretation

The smooth crop-share problem also has a natural acre-level interpretation. Suppose each acre $a \in L_i$ is assigned to the crop that maximizes

$$\pi_{ikt} - a w_{ikt} MC_{it}^{GW} + \nu \varepsilon_{akt}, \tag{34}$$

where ε_{akt} is an acre–crop-specific Type-I extreme-value shock. The shock can represent unobserved acre-level heterogeneity in soil, topography, crop-rotation suitability, or other factors affecting the relative profitability of crops.

Strictly, changing the crop grown on one acre also changes total groundwater pumping and its marginal cost. For a single acre, however, this change is small relative to total pumping by the agricultural user. Evaluating groundwater marginal cost at the aggregate choice GW_{it} gives the local approximation

$$k^*(a) = \arg\max_{k \in K} \left\{ \pi_{ikt} - \Gamma_{ikt} + \nu \varepsilon_{akt} \right\}. \tag{35}$$

Under the Type-I extreme-value assumption, the probability that acre a is allocated to crop k is

$$\mathbb{P}\left(k^*(a) = k\right) = \frac{\exp\left\{(\pi_{ikt} - \Gamma_{ikt})/\nu\right\}}{\sum_{j \in K} \exp\left\{(\pi_{ijt} - \Gamma_{ijt})/\nu\right\}}. \tag{36}$$

With many acres, this choice probability corresponds to the acreage share s_{ikt} and coincides with the solution to the smooth crop-share problem above.

The entropy formulation can be interpreted either as a reduced-form cost of adjusting and concentrating crop acreage or, locally, as the aggregate representation of heterogeneous acre-level crop choices. In either interpretation, ν governs the responsiveness of crop allocation to differences in crop profitability and groundwater costs.

B Trade Model Estimation and Fit

This appendix provides additional details on the simulation and estimation of the bilateral trading model described in Section 6.3. For a candidate vector of transaction-cost parameters, the model generates trade by sequentially evaluating potential bilateral transactions. I use the resulting simulated trades to construct the moments used in simulated method of moments (SMM) estimation and then compare these moments with their empirical counterparts.

B.1 Simulation Algorithm and Moment Construction

Recall that a potential trading pair consists of an agricultural seller s, a water asset held by the seller, and a buyer b, who may be either an agricultural or urban water user. Let θ collect the parameters of the bilateral transaction-cost function,

$$\tau_{sbt}(\theta) = \mu_{u(b)} + \beta_R \text{Right}_{sbt} + \beta_P \text{ProjectExport}_{sbt} + \beta_D \text{CrossDelta}_{sbt} + \beta_d \text{Distance}_{sb} + \psi_{r(s)} - \psi_{r(b)} + \sigma_\tau \varepsilon_{sbt}, \tag{37}$$

where $\mu_{u(b)}$ are buyer-use fixed effects, ψ_r are hydrologic-region terms, and ε_{sbt} is an i.i.d. bilateral transaction-cost shock. The remaining variables and parameters correspond to the institutional and geographic frictions described in Section 6.3.

For any pair, let W_{st} and W_{bt} denote the current surface-water holdings of the seller and buyer and let W_{skt} denote the seller's remaining holdings of water asset k. Regulatory and hydrological constraints determine the fraction α_{sbt} of the seller's reduction in diversions that can be delivered to the buyer. Conditional on current holdings, the bilateral trade quantity solves

$$w^*_{sbt} = \underset{0 \le w \le W_{skt}}{\arg\max} \Big\{ V_{st}(W_{st} - w) - V_{st}(W_{st}) + V_{bt}(W_{bt} + \alpha_{sbt} w) - V_{bt}(W_{bt}) - \tau_{sbt}(\theta) w \Big\}. \tag{38}$$

The bilateral problem depends on current rather than initial water holdings. Consequently, earlier transactions change the marginal values and feasible water supplies relevant for later transactions. Rather than impose a particular ordering of bilateral negotiations, I integrate over this path dependence by randomly ordering potential trading pairs in each simulation.

For a given parameter vector θ, bilateral transaction-cost shocks ε, and random ordering σ, simulated trades and moments are constructed according to Algorithm 1.

Algorithm 1: Simulation of Bilateral Trade and Estimation Moments

Data: Initial water holdings and value functions; regulatory constraints; transaction-cost parameters θ; bilateral shocks ε; random ordering of potential trading pairs σ

Initialize water holdings at their observed pre-trade levels;

for *each potential pair* (s, b) *in the order* σ **do**

  Compute w^*_{sbt} from Equation (38) using current water holdings;

  Update the seller's holdings:

$$W_{st} \leftarrow W_{st} - w^*_{sbt}, \qquad W_{skt} \leftarrow W_{skt} - w^*_{sbt};$$

  Update the buyer's holdings:

$$W_{bt} \leftarrow W_{bt} + \alpha_{sbt} w^*_{sbt};$$

  Record the transaction for the trade-volume, net-trade, and distance moments;

Construct the simulated trade-flow data and estimate the residual-variance moment;

Result: Simulated moment vector $\widehat{M}(\theta, \varepsilon, \sigma)$

This procedure captures two features of the decentralized market that are important for estimation. First, agents may participate in multiple trades, so a transaction changes the water available for subsequent sales or purchases. Second, marginal water values change with these holdings. The random ordering affects the realized allocation even for a fixed draw of transaction costs. Averaging across orderings integrates over this source of path dependence rather than selecting a particular sequence of bilateral negotiations.

I match 15 moments that summarize the principal patterns of observed water trade. The moments consist of: (i) average annual trade volume for five transaction characteristics—agriculture-to-agriculture, agriculture-to-city, transfers of water rights, exports of project water, and trades crossing the Delta; (ii) the quantity-weighted average distance of observed trades; (iii) net trade, defined as imports less exports, for each of the eight hydrologic regions represented in the estimation sample; and (iv) the residual variance from the trade-flow regression described in Section 5.2, re-estimated using the simulated trade flows.

These moments are chosen to correspond closely to the components of the transaction-cost specification. Trade volumes across agricultural and urban buyers primarily discipline the buyer-use fixed effects $\mu_{u(b)}$. Differences in trade involving water rights, project exports, and Delta crossings discipline β_R, β_P, and β_D, respectively. The quantity-weighted distance moment disciplines β_d, while regional net imports discipline the hydrologic-region terms ψ_r. Finally, dispersion in simulated bilateral trade flows disciplines σ_τ. Identification is joint because changing any transaction cost can alter the sequence and composition of subsequent trades.

B.2 Model Fit

Table 9 compares the empirical moments with their simulated counterparts evaluated at the estimated parameters. Because these are the moments entering the SMM objective, the table provides a direct assessment of the model's ability to reproduce the dimensions of observed trade used to estimate bilateral trading frictions.

The model reproduces the broad composition and geography of observed water trade. For example, average agriculture-to-agriculture trade is 305.5 TAF in the data and 286.7 TAF in the model, while agriculture-to-city trade is 18.4 TAF in the data and 22.8 TAF in the model. The model also closely matches trade associated with water rights, project exports, and Delta crossings. Regional net-trade patterns are reproduced particularly closely outside the two largest trading regions; in the Sacramento River region, for example, average net exports are 474.2 TAF in the data and 435.9 TAF in the model. The model generates a quantity-weighted average trading distance of 120.4 miles, compared with 131.5 miles in the data, and a residual variance of 4.42, compared with 4.17 in the data.

Table 9: Trade Model Estimates and Fit

Moment	Data	Model	Parameter	Estimate
Institutional Trade Volumes (TAF)			*Institutional Frictions ($/AF)*	
Water Right	13.8	15.0	Water Right (β_R)	54.42
Project Export	20.6	19.1	Project Export (β_P)	29.11
Cross Delta	121.2	115.1	Cross Delta (β_D)	10.79
Trade by Buyer Type (TAF)			*Buyer-Type Frictions*	
Ag-to-Ag	305.5	286.7	Ag Buyer (μ_{Ag})	[estimate]
Ag-to-City	18.4	22.8	City Buyer (μ_{City})	[estimate]
Average Net Trade by Region (TAF)			*Regional Effects*	
Central Coast	4.3	4.3	Central Coast (ψ_{CC})	[estimate]
Colorado River	3.0	2.9	Colorado River (ψ_{CR})	[estimate]
Sacramento River	-474.2	-435.9	Sacramento River (ψ_{SR})	[estimate]
San Francisco Bay	20.0	19.5	San Francisco Bay (ψ_{SFB})	[estimate]
San Joaquin River	-172.0	-170.1	San Joaquin River (ψ_{SJR})	[estimate]
South Coast	6.7	6.6	South Coast (ψ_{SC})	[estimate]
South Lahontan	13.4	11.8	South Lahontan (ψ_{SL})	[estimate]
Tulare Lake	598.8	560.9	Tulare Lake (ψ_{TL})	[estimate]
Other Moments			*Other Parameters*	
Average Distance (miles)	131.49	120.35	Distance, 100 miles (β_d)	35.54
Residual Variance	4.17	4.42	Residual SD (σ_τ)	[estimate]

Notes: The table reports the 15 empirical moments used in the simulated method of moments estimation, their simulated counterparts evaluated at the estimated parameters, and the corresponding parameter estimates. The simulated market includes agricultural sellers and agricultural or urban buyers; city-originating transactions are excluded. Trade-volume moments are annual averages. Average distance is weighted by transaction quantity, and regional net trade is defined as imports less exports. Institutional and distance parameters are reported in dollars per acre-foot.

C Return-Flow Externalities and Regulation

This appendix provides additional details on the measurement of return-flow externalities and the alternative regulations considered in Section 8. Online Appendix Section B.1 describes estimation of the underlying return-flow network.

C.1 Return-Flow Externalities

For each agricultural DAUCO i and year t, I construct a consumptive-use share α_{it} from the observed crop mix. Specifically, α_{it} is the average consumptive-use share of the crops grown in the DAUCO. Under seller-specific return-flow regulation, a seller reducing its diversion by w acre-feet can transfer $\alpha_{it}w$ acre-feet. The remaining $(1 - \alpha_{it})w$ represents non-consumptive use that may contribute to downstream return flows.

I use the estimated return-flow network to map changes in surface-water use at each source into changes in water available to downstream agricultural, urban, and environmental uses. Let r_{id} denote the estimated change in water available to downstream use d from a one-acre-foot change in surface-water use at source i. Online Appendix Section B.1.1 describes construction of r_{id}. For a set of changes in surface-water use $\{\Delta SW_i\}$, these coefficients determine the resulting change in water available to each downstream use.

$$E_{dt} = V_{dt}(W_{dt}) - V_{dt}(W_{dt} + \Delta W_{dt}). \quad (39)$$

I sum these losses across affected downstream users. Environmental effects are tracked separately in physical units and include changes in instream-flow requirements, managed wetlands, wild and scenic flows, and required Delta outflow. I calculate the marginal externality of each relevant potential transfer by propagating the seller's marginal effect through the return-flow network and valuing downstream losses using Equation (39). The mean of these marginal externalities is \$35.20 per acre-foot, which I apply uniformly across trades. This is a mean-externality tax rather than a transaction-specific Pigouvian tax: individual transfers may generate externalities above or below \$35.20 per acre-foot. Additional details on the construction of the physical return-flow effects are provided in Online Appendix Section B.1.

Online Appendix

Trade Frictions in Surface Water Markets

This Online Appendix contains supplementary derivations, estimation details, data-construction procedures, counterfactual implementation details, and additional results for the paper.

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A Data Construction

A.1 Agricultural Land and Water Use

This paper uses California's Department of Water Resources Land and Water Use datasets from 2002 to 2020, organized at the DAUCO (Design Analysis Unit by County) level by crop and year.

Key variables: irrigated acres (ICA), applied water per acre (AW), evapotranspiration of applied water per acre (ETAW), and effective precipitation per acre (EP).

Datasource Information: The DWR Land and Water Use dataset is produced by the California Department of Water Resources and is publicly available. It contains detailed estimates on land use, water use, and crop-specific water requirements across different regions and time periods within California. The data is collected through a combination of surveys, remote sensing, and field studies. Surveyors use Geographic Information Systems (GIS) and satellite imagery to categorize land cover and usage (e.g., crop types, irrigated areas). This spatial information is cross-referenced with reported water usage data from water districts, irrigation districts, and other sources to estimate water application rates across various crops and regions.

Data cleaning: Adjustments made to address data gaps, anomalous values, and missing information are listed below.

1. To handle cases where irrigated crop area (ICA) values were zero, the values for AW, ETAW, and EP were also set to zero to reflect the absence of water application.

2. In cases where the consumptive share, calculated as the ratio of ETAW to AW, this ratio exceeded 1, the values of AW and ETAW were swapped to correct likely entry errors.

3. Missing consumptive share values were filled using fallback averages from DAUCO, county, or state levels, which ensured consistency across the dataset.

A.2 Urban Water Demand

This paper uses water utility data collected by the American Water Works Association (AWWA) for California utilities from 2016-2022.

Key variables: total volume of water supplied, water sourced from owned and imported supplies, the volume exported, service connections, annual costs, unit costs, and infrastructure characteristics such as pipe length.

Datasource Information: California's Department of Water Resources (DWR) mandates urban retail water suppliers to submit validated water loss audits annually, utilizing the American Water Works Association (AWWA) methodology. These audits are accessible through DWR's Water Use Efficiency Data portal. The AWWA methodology encompasses detailed components from each utility's annual water audit by capturing data from multiple inputs and outputs within the water distribution system.

Data cleaning: The following modifications were made to the dataset to ensure consistency remove missing or implausible values, and align with the study's requirements.

1. Observations missing supplier identifiers, were excluded, ensuring all entries corresponded to identifiable utilities.

2. Only observations with complete data on service connections, total volume supplied, and annual costs were retained.

3. Observations where unit costs were reported in units other than acre-feet were converted using appropriate factors (e.g., gallons to acre-feet).

4. Outlier checks were conducted on unit costs by calculating an average unit cost per utility across all years, then filtering out extreme values exceeding 10 times the utility's mean unit cost.

5. Utilities with reported water supply volumes below 1,000 acre-feet or fewer than 5,000 service connections were removed to focus on significant urban utilities.

A.3 Groundwater Depth

This paper uses data from the California Department of Water Resources (DWR) on groundwater basins at the Well × Timestamp level.

Key Variables: depth to groundwater, surface area of basin.

Datasource Information: The DWR Periodic Groundwater Levels dataset includes groundwater measurements across California's groundwater basins, collected by the DWR and cooperating agencies. Data from the Sustainable Groundwater Management Act (SGMA) and CASGEM programs are also incorporated. The dataset contains seasonal, monthly, and daily readings from DWR's automated network. This dataset includes well-specific details on location, measurement time/date, depth to groundwater, and well construction. The corresponding shapefiles for groundwater basins include the surface area of the basin.

Data cleaning: I use this data to create a DAUCO × Year panel of groundwater depth from 2005-2015. The panel also includes the basin surface area, which is of course fixed across years. Since data are at the Well × Timestamp level, I now describe how this is aggregated.

1. For each Well × Year , I compute the average groundwater depth H_{wt}.
2. For each DAUCO × Year, I compute the average groundwater depth across wells within the DAUCO, $H_{it} = \frac{1}{|w \in i|} \sum_{w \in i} H_{wt}$.
3. There are some DAUCOs where I don't observe any wells, but I do observe groundwater pumping and underlying groundwater basins. So I also compute for each Basin × Year, the average groundwater depth across wells $H_{bt} = \frac{1}{|w \in b|} \sum_{w \in b} H_{wt}$.
4. For DAUCOs that do not have any observations (across years) from step (2), I compute the average DAUCO groundwater depth by weighting basin depth by overlapping area, $H_{it} = \sum_{i \in b} \phi_{i,b} H_{bt}$.
5. Through this process, there are some years unobserved within a DAUCO. For missing years, I do the following for each DAUCO-missing year.
   (a) Compute percentile of depth across DAUCOs for previous and following year.
   (b) Linearly interpolate percentile in the missing year.
   (c) Impute that DAUCOs depth by computing that percentile of statewide depth distribution.

Alongside this panel of groundwater depths, the surface area of each groundwater basin is listed in the shapefile data.

A.4 Surface-Water Transfers

This paper uses a dataset of surface water transfers in California provided by the Public Policy Institute of California (PPIC).

Key Variables: water volume traded, transaction type, buyer, seller.

Datasource Information: The PPIC surface water transfer data is at the Transaction × Year level and aggregates records from major water projects, including the State Water Project (SWP) and Central Valley Project (CVP), provided by the California Department of Water Resources (DWR) and the US Bureau of Reclamation (USBR). Colorado River project data is also included. Further the PPIC collected data from NEPA environmental assessments, the State Water Board's Water Transfers database, and permits for instream flow dedications. Transactions were cross-referenced and verified with other sources with additional verification through direct agency contacts as needed.

Data cleaning: The following steps give us a panel from 2005-2015 of surface water transfers between agents (DAUCOs and utilities) in our sample.

1. I exclude transfers of the following types (e.g., "pool," "bank," "deferred exchange") and environmental transfers as they represent either state programs for saving water or dynamic option contracts, which my model of bilateral trade cannot speak to. Less than 3% of transfers took place in these categories from 2005-2015.

2. The data include yearly leases and long-term transfers. For all transfers that have longer duration than a single year, I average the deliveries across all years and assume a transfer of that size took place in the first year of the long-term transfer. This is because I think of transaction costs as occurring in the first year of negotiations and approval, and not each year that water is transported. It is likely that long-term transfers are subject to higher transaction costs than short term transfers, but I do not address this force in this paper so as to avoid a dynamic model of trade.

3. Indicators for within-project (e.g., both buyer and seller are SWP participants) or cross-project transfers (e.g., SWP to CVP) were added depending on the SWP or CVP status of the trading partners.

4. Transfers crossing geographic regions (e.g., crossing the Delta) were flagged using origin and destination region data.

5. To assign transfers from trading agents, which are not at the same aggregation as DAUCOs and utilities, I overlap transfer participant shapefiles with my agency shapefiles and distribute transfers relative to size of overlapping areas.

A.5 Hydrological and Conveyance Networks

This paper uses the National Hydrography Dataset (NHD) and other supplementary data on canal infrastructure. I want to create a network between all DAUCOs and utilities where the edges represent rivers or canals and the weights on the edges represent distance in miles.

Key Variables: shortest distance between agents.

Datasource Information: The hydrological network data utilizes the U.S. Environmental Protection Agency's (EPA) National Hydrography Dataset (NHD), managed by the EPA Office of Water. The NHDPlusV2 dataset provides comprehensive information on streamflow and hydrological connectivity across the U.S., including high-resolution data on

California's natural river systems. This dataset integrates physical characteristics of water bodies, flow direction, and connectivity data to support modeling of interconnected river networks. Cross-regional canal and aqueduct information was compiled from multiple state and federal datasets, covering major conveyance systems like California's aqueducts. Additionally, urban water district and irrigation district shapefiles were used to identify intra-district infrastructure, capturing more granular conveyance paths within district boundaries. By integrating cross-regional and intra-district datasets, a comprehensive conveyance network was constructed, linking Design Analysis Unit by County (DAUCO) regions across both natural and artificial water conveyance paths.

Data cleaning: The following steps outline the construction of the DAUCO hydrological network from the raw data, including methods for calculating distances across the network.

1. Constructing the Natural Flow Network: Flowline shapefiles from the NHDPlusV2 dataset were loaded to capture natural river connections between nodes, identified by coordinates.

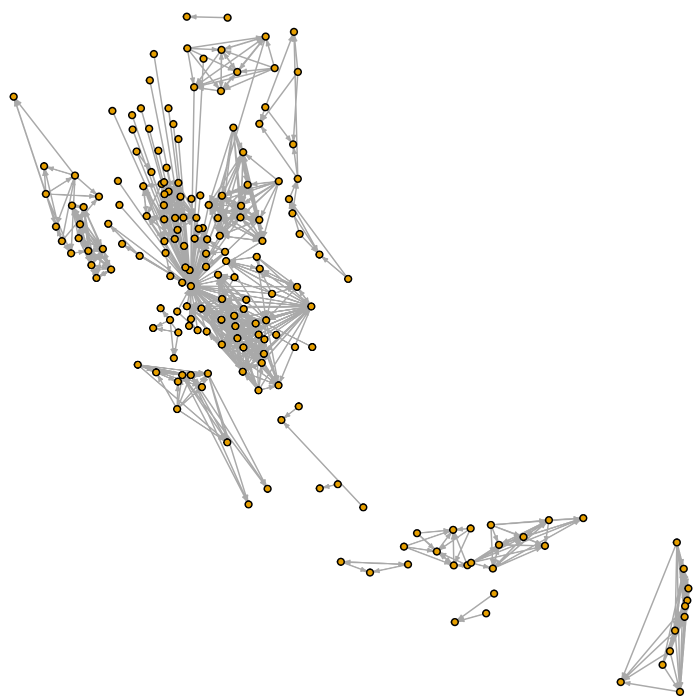
2. Establishing DAUCO Nodes: I linked flowline coordinates to DAUCOs by spatial matching. Using the order of flowline segments, I directed the natural river flow from DAUCO to DAUCO.

3. Incorporating Artificial Infrastructure: From the supplementary canal infrastructure shapefiles, I hand coded the direction of each canal. I then combined the spatial match of these canals with networks to direct edges and incorporate with the river data to construct an integrated hydrological network. Within district shapefiles I assume a connected network even if no canal infrastructure is observed.

4. Creating Network Edges: For each river or canal segment, I identified upstream and downstream DAUCOs, allowing for the creation of directional edges. I filtered natural river segments to only those with flow over 1 taf per year, ensuring that minor connections did not overly complicate the network.

5. Computing Distances on the Network: Using the constructed network, shortest path distances were calculated between DAUCO nodes. The distances were computed based on edge weights, reflecting hydrological distances across both natural and artificial infrastructure. I included utilities in the network by assigning utilities to the DAUCO which had the greatest overlapping area.

Figure A.1: Return Flow Network



Notes: Figure shows the network of return flow contributions between DAUCOs. An arrow indicates that some share of return flow is contributed from the origin to the destination DAUCO. These edges and their associated weights are estimated according to the procedure described in Section B.1.

B Additional Estimation and Computational Details

B.1 Return Flow Network Estimation

To evaluate the impact of return flow management on water supply, I estimate a network of return flow contributions and dependence between DAUCOs. The Department of Water Resources (DWR) water balance data includes data on return flow contributions and dependence at the within DAUCO, within Planning Area (PA), within hydrologic region, and intra-region level. Within each level of aggregation, I model the return flow contributions depenence as follows and estimate the (DAUCO $\times$ Use)-to-(DAUCO $\times$ Use) level return flow network.

Let S_{ikjht} be the quantity of return flow that water use k on DAUCO i contributes to DAUCO j's water use h in year t. I do not observe all S_{ikjht}, but I have data on aggregated return flow supply and dependence at the DAUCO-dependent-nested planning areas, hydrologic regions, and California. For aggregated groups G I observe:

$$S_{ikt}(G) = \sum_{h} \sum_{j \in G, j \neq i} S_{ikjht} \tag{B.1}$$

$$D_{jht}(G) = \sum_{k} \sum_{i \in G, i \neq j} S_{ikjht} \tag{B.2}$$

I estimate S_{ikjht} using the DWR Water Balance data I have from 2002-2020 by making the following assumption:

$$S_{ikjht} = \lambda_G(i,k,j,h) S_{ikt}(G) \tag{B.3}$$

Parameter $\lambda_G(i,k,j,h)$ represents the share of $S_{ikt}(G)$ that contributes to DAUCO j's use h.

For each G, I estimate return flow shares parameters λ by:

$$\lambda_G \sum_{j \in G} \sum_{h} \left(D_{jht}(G) - \sum_{i \in G, i \neq j} \sum_{k} \lambda_G(i,k,j,h) S_{ikt} \right)^2 \tag{B.4}$$

$$\text{s.t.} \quad \sum_{j \in G, j \neq i} \sum_{h} \lambda_G(i,k,j,h) = 1, \text{ for all } i \in G \text{ and } k. \tag{B.5}$$

$$\lambda_G(i,k,j,h) \geq 0. \tag{B.6}$$

While it looks like there are many more parameters than data, I do not have to estimate all potential combinations of inputs to λ. Within each grouping G, I must estimate λ for each potential supplier-depender pair within the group. DAUCO-uses are potential suppliers/dependers if that DAUCO-use ever supplies or depends on return flow. The number of suppliers and dependers are:

$$N_G^S = \sum_{i \in G} \sum_k \mathbf{1}\Big[\sum_t S_{ikt}(G) > 0\Big] \tag{B.7}$$

$$N_G^D = \sum_{j \in G} \sum_h \mathbf{1}\Big[\sum_t D_{jht}(G) > 0\Big] \tag{B.8}$$

Therefore, the total number of parameters in each group I need to estimate is $M_G = N_G^S \times N_G^D$. The number of observations is $T \times (N_G^S + N_G^D)$.

In Appendix Figure A.1 I depict whenever there exists a DAUCO-to-DAUCO level return flow dependency. The direction of the edge represents the contributor and the dependent DAUCO. This network obscures information about the use-to-use level contributions which are contained in the estimated $\lambda_G(i, k, j, h)$ parameters. In counterfactuals where return flows are not internalized, I use the estimated return flow network along with the estimated parameters to comptue which agents are affected by how much. I incorporate utilities in the network by matching utilities to the DAUCO with the most overlapping area.

B.1.1 Mapping Return Flows into Downstream Water Effects

I use the estimated return-flow network to construct the marginal effect of surface-water use at each source on water available at each downstream use. Let λ_{id} denote the estimated network share mapping return flow generated at source i to downstream use d.

Not all non-consumptive applied water appears as return flow. For each agricultural source, I therefore construct the return-flow realization rate

$$\rho_i = \frac{RF_i}{(1 - \alpha_i) AW_i}, \tag{B.9}$$

where RF_i is observed return flow, AW_i is applied water, and α_i is the crop-weighted consumptive-use share. I calculate this quantity using 2012–2015 observations, average it within source locations, and cap it at one.

Combining the estimated network with this realization rate gives the marginal downstream effect of changes in surface-water use. Specifically, for each source i and downstream use d, I construct

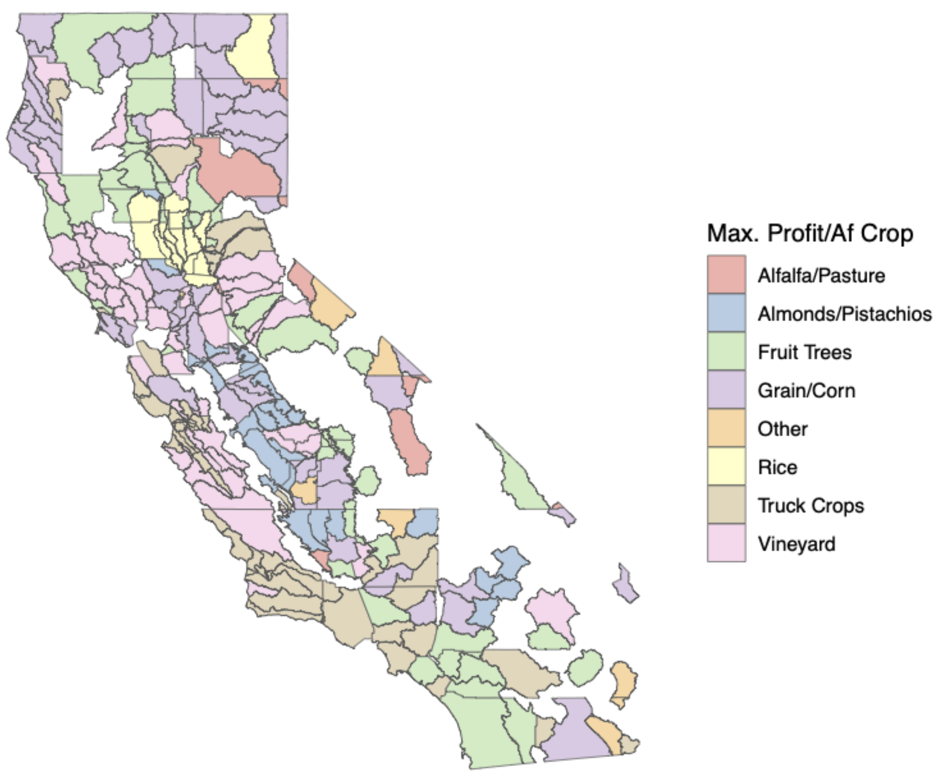
$$r_{id} = \lambda_{id} \rho_i (1 - \alpha_i) g_{id}, \tag{B.10}$$

where g_{id} is the allocation share defined in the return-flow estimation above. These coefficients map counterfactual changes in surface-water use into changes in water availability at downstream agricultural, urban, and environmental uses.

For water directly preserved in the hydrological system by a regulatory adjustment, I use the corresponding network mapping without the empirical return-flow realization rate. This distinguishes changes in return flows generated by water use from water directly left in the system by the regulatory adjustment.

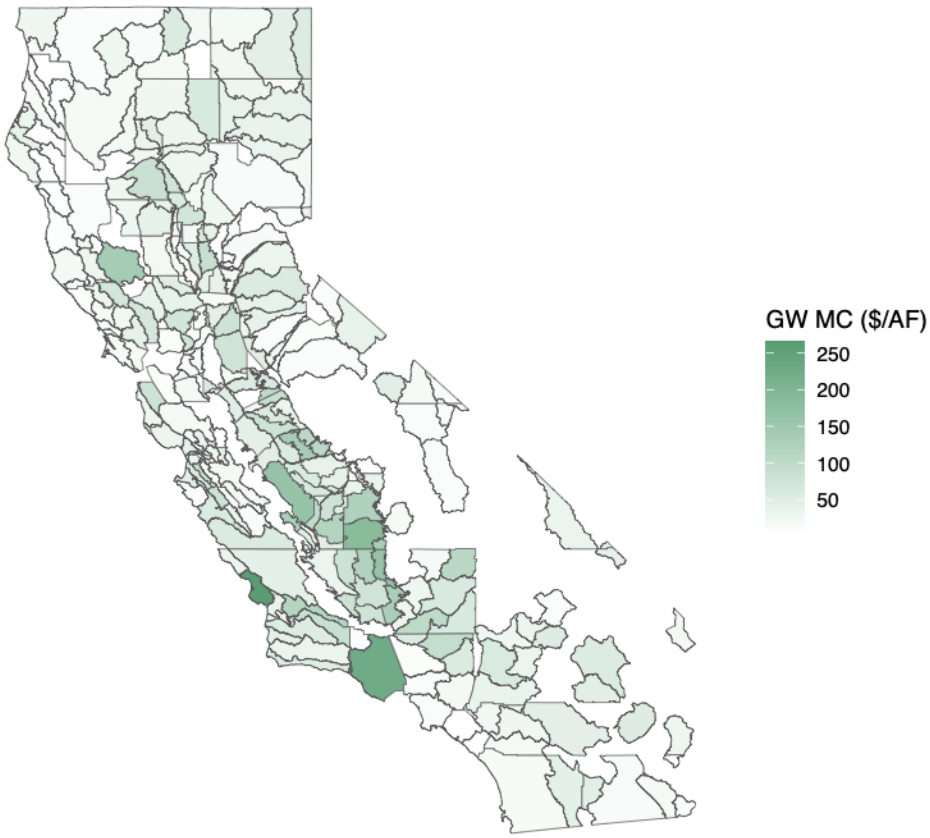
B.2 Agricultural Estimation Details

Figure B.1: Profit/af Maximizing Crops



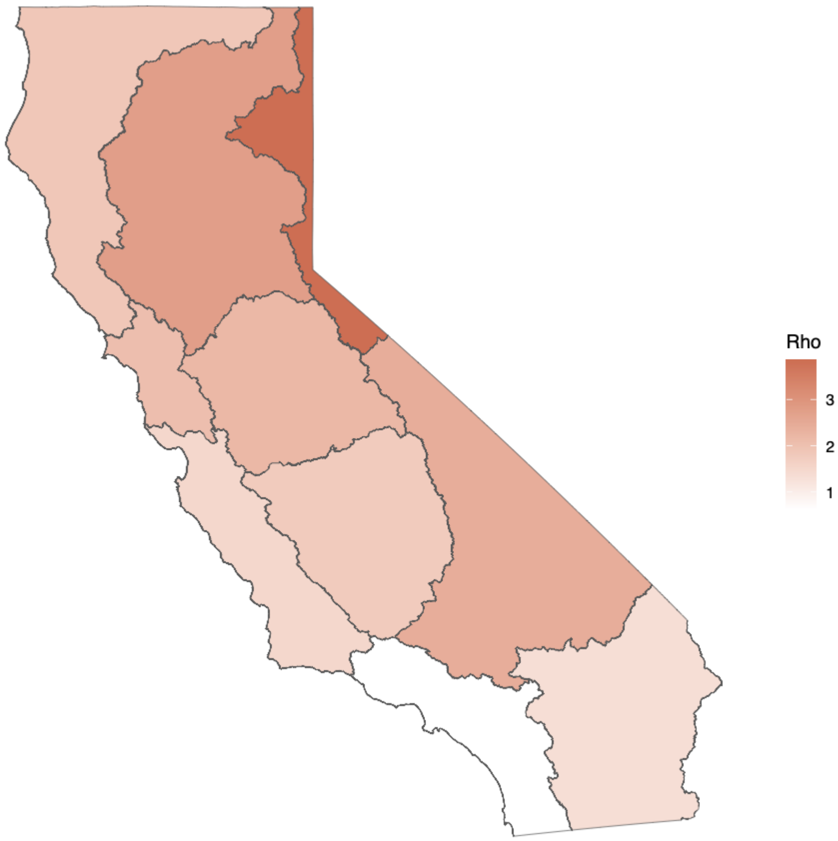
Notes: Figure depicts for each DAUCO the crop with the largest average profit per acre-foot. Profit parameters are estimated as in Table 4. Profits are averaged over years 2005-2015.

Figure B.2: Marginal Cost of GW



Notes: Figure depicts the estimated average marginal cost of groundwater, which is equivalent to agricultural marginal willingness-to-apy, for each DAUCO. Marginal costs are averaged over years 2005-2015 and estimated as specified in Table 4.

Figure B.3: Pumping Efficiency (kWh / af × foot)



Notes: Figure depicts the estimated regional pumping efficieny parameters which are in kWh per acre-foot per foot height pumped. Pumping efficiency ρ is as estimated in Table 4.

Table B.1: Crop Applied Water Requirements

	Mean	p10	p50	p90
af/acre				
Alfalfa	5.61	3.76	5.48	7.72
Almonds/Pistachios	4.29	3.41	4.31	5.04
Citrus/Subtropical	4.03	2.72	3.83	5.38
Corn	2.76	2.26	2.71	3.34
Cotton	3.47	2.74	3.33	4.08
Cucurbits	2.5	1.57	2.48	3.58
Dry Beans	2.34	1.79	2.31	2.91
Fresh Tomato	2.11	1.57	1.99	2.73
Grain	1.7	0.67	1.61	2.66
Onion/Garlic	3.28	2.39	3.26	4.11
Other Deciduous	3.94	3.15	3.9	4.85
Other Field	2.97	2.35	2.96	3.44
Pasture	4.92	3.06	4.7	6.95
Potato	2.81	1.5	2.36	4.59
Processing Tomato	2.66	2.19	2.68	3.16
Rice	4.28	2.88	4.89	5.26
Safflower	2.04	0.965	2.29	2.69
Truck Crops	2.17	1.02	1.87	3.81
Vineyard	3.08	1.59	2.98	4.41

Notes: Table summarizes DAUCO-year data from 2005 and 2015 on applied water per acre across crop categories. For each crop, I report the mean, 10th, median, and 90th percentiles of applied water requirements across crops.

B.3 Approximation of Value Functions

The estimated surface water value functions for DAUCOs in Equation 8 and for utilities in Equation 10 do not allow for closed form computation of the optimal bilateral trade $w^*(W_{st}, W_{skt}, W_{bt}, \alpha(b, s), \theta)$ described in the trade algorithm. Numerically computing the optimal trade for every pair within the trading simulation is not reasonable computationally. For this reason, I approximate the estimated DAUCO and utility willingness-to-pay functions.

On the agricultural side, I approximate marginal willingness-to-pay, the derivative of a DAUCOs value function described in Equation 8, with a linear function:

$$\widetilde{MV}_{it}(W) = 2a_{it}W + b_{it} \tag{B.11}$$

For each DAUCO-year, I define a_{it} and b_{it} so that the estimated marginal values and the approximation match at the observed surface water endowment and when estimated marginal value is zero. Let $W_{it}^{max} =_W V_{it}(W)$. Since DAUCOs are limited to the total land and experience entropy costs as fallowing share approaches zero, this maximum demand for surface water has a finite solution. Therefore, the conditions to pin down approximation parameters a_{it} and b_{it} are:

$$MV_{it}(W_{it}) = 2a_{it}W_{it} + b_{it} \tag{B.12}$$

$$0 = 2a_{it}W_{it}^{max} + b_{it}. \tag{B.13}$$

Note that the estimated marginal value $MV_{it}(W_{it})$ is precisely the marginal cost of groundwater in year t for DAUCO i. The integral of this approximation closely aligns with the estimated value function for DAUCOs.

However, for cities, the utility value function is not as closely approximated by the exact same approach. Instead, we approximate urban values with piecewise linear marginal values with a break at the observed surface water supply.

$$\widetilde{MV}_{it}(W) = \begin{cases} 2a_{it}^{L}W + b_{it}^{L} & W \leq W_{it} \\ 2a_{it}^{H}W + b_{it}^{H} & W > W_{it} \end{cases} \tag{B.14}$$

The conditions to pin down approximation parameters a_{it}^H, b_{it}^H, a_{it}^L, and b_{it}^L are:

$$MV_{it}(W_{it}) = 2a_{it}^{H}W_{it} + b_{it}^{H} = 2a_{it}^{L}W_{it} + b_{it}^{L} \tag{B.15}$$

$$0 = 2a_{it}^{H}W_{it}^{max} + b_{it}^{H} \tag{B.16}$$

$$MV_{it}\left(\frac{W_{it}}{4}\right) = 2a_{it}^{L}\frac{W_{it}}{4} + b_{it}^{L} \tag{B.17}$$

Where the estimated utility $MV_{it}(\cdot)$ can be computed directly from the urban demand estimation along with the W_{it}^{max} that sets that marginal value to zero.

Given these approximation parameters, I compute optimal bilateral trades w^* in the trade simulation by the following.

$$
\begin{aligned}
w^* =_w & \Big(a^L_{st}(W_{st} - w)^2 - a^L_{st}(W_{st})^2 - b^L_{st} w\Big) \\
& + \Big(a^H_{bt}(W_{bt} + \alpha(s,b)w)^2 - a^H_{bt}(W_{bt})^2 + \alpha(s,b) b^H_{st} w\Big) \\
& - \tau_{sbt}(\theta) w \qquad \text{s.t } 0 \leq w \leq W_{skt}.
\end{aligned}
$$

Where for DAUCOs, $a^L_{it} = a^H_{it}$ and $b^L_{it} = b^H_{it}$. So that the kink in urban approximation does not cause problems, once a utility participates in a trade, they remain on either the buyer or seller side for all remaining trade considerations. This constrained optimization problem has a solution that is linear in parameters with boundary conditions and facilitates estimation, which requires the iterative solution of this problem across many trading partners.

B.4 Urban Water-Asset Imputation

Computing quantity by type of water asset W_{ikt} for each agent is easy for agricultural DAUCOs which report this quantity. For urban utilities, which do not breakdown water sources in my dataset, I impute the decomposition of surface water supply sources by using DAUCO-level urban water use quantities from the DWR water balance dataset.

For each utility, I compute the share of water that comes form each water asset by aggregating all overlapping DAUCO urban supply shares, weighted by overlapping area.

C Counterfactual Implementation

This section describes the implementation of the counterfactuals reported in Section 8. The exercises alter particular components of the estimated trading environment while holding all other primitives and estimated parameters fixed. I first describe the institutional reform counterfactuals and then the alternative approaches to regulating return-flow externalities.

C.1 Market Reform Counterfactuals

The market-reform counterfactuals alter three features of the baseline trading environment: the incremental friction associated with transfers of water rights, the incremental friction associated with determining and approving return-flow adjustments, and the restrictions associated with moving water through the Delta.

Let β_R denote the estimated incremental friction associated with transfers of water rights, β_P the incremental friction associated with project exports and return-flow determination, and β_D the incremental friction associated with trades crossing the Delta. In the estimates reported in the paper,

$$\widehat{\beta}_R = 54.42, \qquad \widehat{\beta}_P = 29.11, \qquad \widehat{\beta}_D = 10.79$$

in dollars per acre-foot.

For trades requiring a return-flow adjustment, let α_{sbt}^{RF} denote the seller-specific fraction of the seller's reduction in diversions that can be delivered to the buyer. Thus, if the seller reduces diversions by w, the buyer receives $\alpha_{sbt}^{RF} w$, prior to any additional conveyance adjustment. In the baseline, α_{sbt}^{RF} is seller specific and is constructed from the estimated consumptive-use and return-flow relationships described in Section B.1.

Trades crossing the Delta are additionally subject to both the estimated Delta-crossing transaction friction and a carriage-water requirement. The Delta reform removes both components. It therefore differs from simply setting $\beta_D = 0$: it also eliminates the reduction in delivered water associated with the carriage-water constraint.

Table C.1 summarizes the institutional changes imposed in each counterfactual.

Table C.1: Implementation of Market Reform Counterfactuals

Counterfactual	Rights friction	RF information friction	RF rule	Delta friction
Baseline	Estimated	Estimated	Seller-specific	Estimated
No RF determination cost	Estimated	Zero	Seller-specific	Estimated
Delta reform	Estimated	Estimated	Seller-specific	Zero
Delta reform + no RF cost	Estimated	Zero	Seller-specific	Zero
Delta reform + rights reform	Zero	Estimated	Seller-specific	Zero
Delta reform + rights reform + no RF cost	Zero	Zero	Seller-specific	Zero

Notes: "Estimated" indicates that the corresponding component is held at its baseline estimated value. "Zero" indicates that the incremental transaction friction is removed. Seller-specific return-flow regulation retains the transaction-specific adjustment to transferable water implied by the seller's estimated consumptive use. The Delta reform removes both the estimated Delta-crossing transaction friction and the carriage-water requirement. The rights reform removes the incremental friction associated with transferring a water right but retains all applicable return-flow protections.

The first counterfactual removes only the incremental cost associated with determining and approving return-flow adjustments while retaining the seller-specific adjustment itself. It therefore isolates the cost of obtaining and implementing transaction-specific return-flow information from the downstream protection that this information permits.

The Delta reform removes both the estimated incremental friction for Delta-crossing trades and the associated carriage-water requirement. The rights reform removes the incremental friction associated with establishing and transferring a water right. Importantly, neither reform removes seller-specific return-flow protection. The combined counterfactuals therefore measure the interaction among these market frictions rather than replacing the existing system with frictionless trade.

C.2 Alternative Return-Flow Regulations

The second set of counterfactuals compares alternative methods of regulating the downstream effects of water transfers. These exercises distinguish the *precision* of return-flow regulation from the other frictions in the market.

I consider four return-flow regimes:

1. **Costly seller-specific regulation.** The regulator uses seller-specific return-flow information to determine α_{sbt}^{RF}, and trades requiring this determination incur the estimated return-flow information friction $\widehat{\beta}_P = 29.11$ dollars per acre-foot.

2. **Costless seller-specific regulation.** The regulator continues to apply the same seller-specific α_{sbt}^{RF}, but the incremental cost of determining and implementing the adjustment is set to zero.

3. **Uniform performance standard.** Seller-specific return-flow information is not used. Instead, all trades subject to return-flow regulation face a common adjustment $\alpha_{sbt}^{RF} = \bar{\alpha}$. I evaluate $\bar{\alpha}$ over a grid between 0.5 and 1.

4. **Uniform mean-externality tax.** The seller-specific quantity adjustment is removed, so $\alpha_{sbt}^{RF} = 1$, and affected trades instead pay a uniform tax equal to the average marginal return-flow externality,
$$t^{RF} = 35.20$$
dollars per acre-foot.

Table C.2 summarizes these four regimes.

Table C.2: Alternative Return-Flow Regulations

Regulatory regime	Seller-specific adjustment	RF information friction	Uniform RF tax
Costly seller-specific	Yes	\$29.11/AF	No
Costless seller-specific	Yes	\$0/AF	No
Uniform performance standard	No: $\alpha^{RF} = \bar{\alpha}$	\$0/AF	No
Uniform mean-externality tax	No: $\alpha^{RF} = 1$	\$0/AF	\$35.20/AF

Notes: Seller-specific regulation uses the estimated return-flow adjustment for each seller. Under the uniform performance standard, all affected transactions receive the same transferable fraction $\bar{\alpha}$. Under the uniform mean-externality tax, the seller-specific quantity restriction is removed and the transaction instead pays a common tax equal to the average estimated marginal return-flow externality. The tax is therefore a coarse uniform tax, not a transaction-specific Pigouvian tax.

Uniform performance standards. For each market environment, I simulate a sequence of common performance standards $\bar{\alpha} \in [0.5, 1]$. A larger value of $\bar{\alpha}$ permits a larger fraction of a seller's reduction in diversions to be transferred to the buyer and is therefore a less restrictive standard.

In addition to displaying the full set of standards, I report the *no-harm* standard. I define the no-harm value as the largest $\bar{\alpha}$ such that the counterfactual causes neither (i) a reduction in environmental water nor (ii) a reduction in water available to any downstream water user relative to the corresponding baseline regulatory environment. The resulting values are

$$\bar{\alpha}^{NH} = \begin{cases} 0.68, & \text{Baseline market environment,} \\ 0.50, & \text{Delta reform,} \\ 0.65, & \text{Delta reform + rights reform.} \end{cases}$$

These values are determined separately because changing other market frictions changes the set and composition of trades generated under a common return-flow standard.

Uniform mean-externality tax. A transaction-specific Pigouvian tax would require the same seller-specific information about downstream effects that is used to implement the precise return-flow adjustment. To evaluate a genuinely coarse alternative, I instead apply a single tax to all transactions subject to return-flow regulation. The tax is fixed at \$35.20 per acre-foot, the average marginal return-flow externality in the baseline model.

Implementing this counterfactual requires separating the return-flow component of the estimated transfer friction from the additional friction associated with transferring a water right. The estimated project-export friction, \$29.11 per acre-foot, is treated as the return-flow information component. The water-right coefficient is \$54.42 per acre-foot, implying an additional rights-specific component of

$$54.42 - 29.11 = 25.31$$

dollars per acre-foot.

Under the uniform-tax counterfactual, I therefore replace the \$29.11 return-flow information component with the \$35.20 tax while preserving the \$25.31 incremental rights-specific component. Equivalently, an affected water-right transfer faces

$$25.31 + 35.20 = 60.51$$

dollars per acre-foot from these two components. I simultaneously remove the seller-specific return-flow quantity adjustment by setting $\alpha_{sbt}^{RF} = 1$. All other transaction costs and constraints are held fixed according to the market environment under consideration.

Market environments. I compare the four return-flow regulations under three configurations of the broader market:

1. the baseline estimated market;
2. the market after the Delta reform; and
3. the market after both the Delta and rights reforms.

This comparison holds the definition of each return-flow regulation fixed while varying the other frictions limiting trade. It therefore measures how the value of transaction-specific return-flow information changes as complementary barriers to trade are relaxed.

References