Trade Frictions in Surface Water Markets

Billy Ferguson
Graduate School of Business
Stanford University
`billyf@stanford.edu`*

Link to Latest Version

Last Updated November 11, 2024

Abstract

This paper studies the barriers to water trade in California's surface water market. Despite significant price disparities between users, less than 5% of surface water is traded annually. Commonly cited frictions include incomplete property rights, costly management of externalities, and infrastructural constraints. I build and estimate a model of California's water market to decompose these frictions and simulate counterfactuals. My model features agricultural production, urban demand, hydrological externalities, and bilateral transaction costs. I find that incomplete property rights and constraints on an important bottleneck in the system represent significant sources of friction. Despite qualitative concern about the regulatory burden of managing externalities, this friction is relatively modest. I estimate that constructing new infrastructure coupled with streamlining water rights management would quadruple trade volume, increase agricultural profits by 10%, and increase environmental water supply. While these interventions reduce misallocation amongst farmers, they do not significantly benefit urban buyers.

---

[*] I am grateful to Lanier Benkard, Paul Milgrom, and Ali Yurukoglu for their advising and support. I also thank Hunt Allcott, Claudia Allende, Bharat Chandar, Cody Cook, Liran Einav, Matthew Gentzkow, Ravi Jagadeesan, Zane Kashner, Brad Ross, Paulo Somaini, Juan Carlos Suarez Serrato, Shoshanna Vasserman, Frank Yang, and seminar participants at Stanford University. I thank Buzz Thompson for nurturing my interest and understanding in water and Ellen Hanak for sharing important data for this project.

1 Introduction

Water is a crucial upstream input to all economic output. While global water demand is expected to increase 20-30% by 2050, a changing climate continues to decrease supply and increase volatility (Boretti & Rosa, 2019). Water trade facilitates efficient climate adaptation, but water markets are virtually non-existent with less than 1% of water claims traded internationally (Rafey, 2023).

In California, limited market activity is especially puzzling given legacy water rights and massive dispersion in water prices. Figure 1(a) depicts the distribution of water prices per acre-foot in California for agricultural and municipal users.[1] Some farmers are over-drafting groundwater basins hundreds of feet deep at costs an order of magnitude higher than other farmers. Urban utility prices for residential consumers also show wide dispersion and are another order of magnitude higher than even the most expensive agricultural water. Despite these large potential gains from trade, surface water trade volumes make up only 1-5% of total surface water supply, as shown in Figure 1(b).

How does California's surface water misallocation persist? A rich qualitative and budding quantitative literature discusses high transaction costs in surface water markets. Since water uses upstream can affect downstream supply, property rights are incomplete, and mismanaged transportation can cause saltwater intrusion, potential water transfers undergo costly evaluation to satisfy constraints and avoid harmful externalities. (Hagerty, 2023, Hanemann & Young, 2020, Leonard, Costello, & Libecap, 2019b, Regnacq, Dinar, & Hanak, 2016, Young, 1986). While the literature suggests that this process is costly, ignoring potential externalities from irresponsible transfers could be prohibitively harmful. Analyses that do not incorporate how surface water transfers can create externalities will overlook real constraints in the system that may require clever market design or infrastructural investment (Colby, 1990).

In this paper, I address surface water's pervasive externality problem, decompose market frictions, and evaluate various policy proposals to alleviate surface water misallocation. I analyze these forces in California's surface water market, which supports the largest population, agricultural economy, and water market in the United States. By creating a comprehensive panel of California's water economy that includes supply sources, farmer irrigation choices, municipal demand, hydrological externalities, infrastructural constraints, and trade, I study counterfactuals that incorporate the structural details of water management. While I leverage many institutional details unique to California, lessons about the trade-off between streamlined transfers, externality management, and environmental needs are applicable to many other large surface water market.[2]

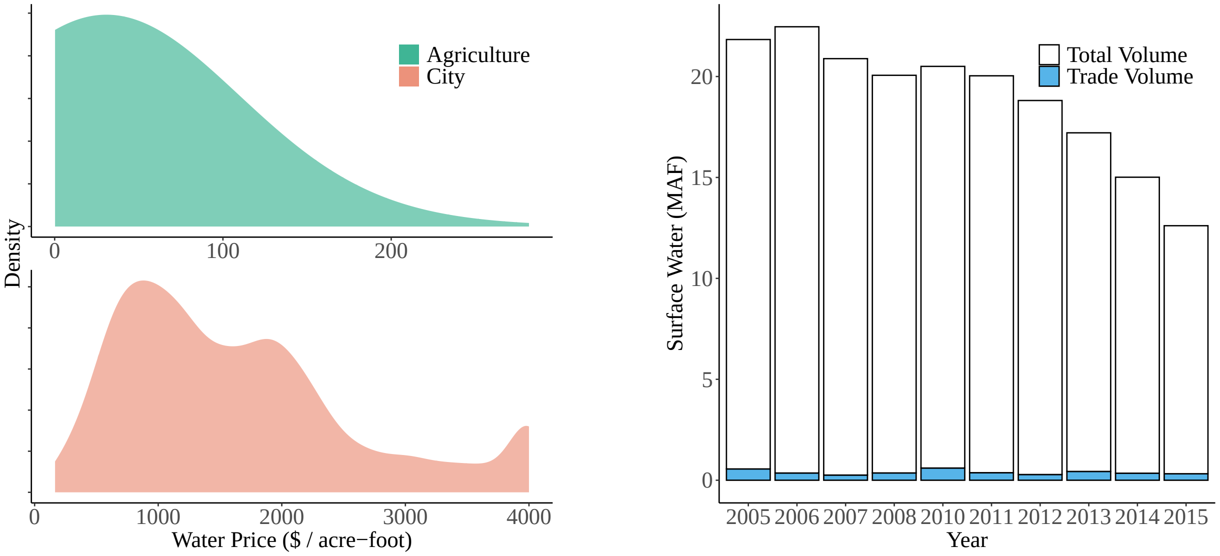
I first provide a stylized example that demonstrates how the structural interconnectedness of water supply makes surface water transfers susceptible to externalities. Managing these externalities is costly due to informational and infrastructural frictions. Due to incomplete information, surface water rights require *rights verification* to determine available quantity and *externality measurement*

---

[1] An acre-foot is the amount of water required to fill an acre of land with a foot of water. Annually, the average family of four in California uses 0.5 acre-feet and the typical crop uses 3 acre-feet per acre.

[2] Chile, Spain, the Colorado River Basin states, and Australia are all large surface water systems that face the same kinds of frictions and design choices.

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 5.1. City prices are average retail prices truncated at $4000. Panel (b) depicts surface water supply and trade in million acre-feet.

to protect downstream supply. Given current infrastructure in *the Delta*, many valuable water transfers are exported out of a delicate ecosystem risking environmental impacts on endangered species and salinity contamination of urban and agricultural supply. An important perspective and contribution of my paper is directly incorporating these constraints so that policy evaluation does not ignore externalities and overstate gains.

To motive my focus on informational and infrastructural constraints, I first provide some descriptive evidence of frictions to surface water trade. I estimate a multinomial logit model of trade shares based on trade characteristics, both with and without structurally estimated gains from trade. Both models show that low trade shares correlate with key frictions: incomplete property rights, potential externalities, and infrastructure limitations. Combined, the magnitude of these frictions is equivalent to nearly two thousand dollars of potential gains from trade. However, these estimates don't distinguish between regulatory constraints and direct transaction costs and aren't suited for policy or welfare analysis.

Decomposing the relative magnitudes of these frictions, the impact of structural constraints, and evaluating alternative policies depends on two empirical objects: willingness-to-pay for surface water and magnitudes of trading constraints. In my model, traders have potential gains from feasible trade where feasibility depends on the surface water supply network and the regulatory constraints imposed to manage externalities. I estimate willingness-to-pay for agricultural agents by observing crop choice and groundwater pumping behavior and for urban agents by estimating residential demand. The set of potential trading agents is restricted to the hydrological network of rivers and canals. Regulatory constraints depend on the geographic distribution of kinds of water assets, crop choices, climate, and hydrogeology of transacting partners.

My agricultural production model focuses on farmers' choices to pump groundwater, change crops, or let land lie fallow in response to surface water shortages. Farmers have the nearly unrestricted option to pump groundwater at a cost.[3] I find that for every acre-foot reduction in surface water, farmers pump an additional 0.85 acre-feet of groundwater, similar to their response to changes in rainfall. I use regional electricity prices and groundwater depth data to estimate the cost of pumping and apply a multinomial crop choice model to determine agricultural willingness-to-pay for surface water, with groundwater cost variation instrumented by surface water rights. I estimate that the average marginal cost of groundwater pumping in California is $54 per acre-foot, though it varies significantly, reaching up to $250 in some areas. This misallocation of surface water by groundwater cost also reflects substantial inefficiency in crop choices, as profits per acre-foot for high-value crops like citrus are four times those of rice.

I estimate urban water demand with a 2016–2022 panel of utility-level quantities and prices. Many utilities rely on a complex wholesale network for surface water access, with some supply from owned rights or long-term contracts. Using utility-owned supply as an instrument, I find urban demand is inelastic to price, with an elasticity of -0.18 at average prices. Adjusting demand for production costs, I estimate the median urban marginal willingness-to-pay for surface water at $524 per acre-foot, notably higher than agricultural values.

To decompose the magnitude of different frictions to transaction costs in California's surface water market, I combine the willingness-to-pay models for agriculture and urban sectors with a trade model. I assume bilateral trade occurs with seller-buyer-year-specific marginal costs, linearly parameterized by transfer characteristics. Bilateral pairs trade until all gains are exhausted. Using 2012–2015 trade flows as moments, I estimate transaction costs via simulated method of moments.

There are four key results. First, I find that transaction costs associated with measuring externalities are about $40/acre-foot. While this friction is nearly 80% of the average agricultural willingness-to-pay for water and can make up about a fifth of trade frictions between farmers, removing this friction, even in years of severe drought, only produces annual gains in agricultural allocative surplus of $15 million. Furthermore, policies that could feasibly eliminate this transaction cost with no-information lower bounds do not noticeably outperform baseline market performance. I view this as an important negative result for water policy design. While there is a strong emphasis on reducing the transaction costs associated with evaluating trade externalities, my findings suggest that there is limited scope for improvement.

Second, if California implements infrastructural investment and constructs a new pipeline, which will eliminate hydrological constraints on trade across the Delta, agricultural surplus will increase by $104.6 million on average in dry years - equivalent to 3% of agricultural profits. Cities only see benefits of $2 million from this policy proposal. While gains are large for agriculture and should

---

[3] Groundwater pumping was largely unregulated until 2014 with the passage of the Sustainable Groundwater Management Act which will not comprehensively regulate pumping until the 2040s.

be considered in the cost-benefit analysis of Delta pipeline construction, these gains alone cannot justify the anticipated construction cost of $20 billion.

Third, the frictions associated with trading incomplete surface water rights are quite large at $404/acre-foot. The annual claims to water according to these rights are unverified prior to trade and limited information is available to potential trading partners. Combining the Delta conveyance project with policies that streamline information about rights could increase agricultural profits by 10% in dry years. Furthermore, a counterfactual that does not require externality measurement could insure no downstream externalities, achieve most of the market gains, and provide an additional 100 thousand acre feet for environmental uses.

Fourth, none of the previously mentioned interventions resolve the large gap in willingness-to-pay between farmers and cities. I estimate that residual frictions associated with transfers where buyers are urban utilities are around $2500/acre-foot. Eliminating this friction alone produces more value than the combination of previous interventions. If each of these frictions can be eliminated, dry years will see statewide gains of $600 million that benefit both farmers and cities equally. Although my analysis doesn't pinpoint specific mechanisms, supply-chain barriers, repugnance to urban transfers, and political factors likely play roles and deserve attention in future research.

My results emphasize the importance of incorporating buyer-seller specific transaction costs and gains from trade subject to hydrological constraints. The structural results suggest a new agenda for water market design that de-emphasizes hydrological barriers and highlights political incentives and supply chain relationships in water management. Administrative costs associated with third-party and environmental externalities are non-trivial, but will not close the largest gaps in value for water in California. Un-clarified, poorly measured, and un-digitized water rights are a significant friction to market performance. Discovering and resolving other frictions for urban buyers may provide the most impactful solutions to market failure in California.

Related Literature: This paper primarily contributes to several literatures in resource and agricultural economics. First, a large literature estimates models of crop choice (Carpentier, Letort, & Stenger, 2015, Carpentier & Letort, 2014, Scott, 2014, Rafey, 2023), 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). I contribute new willingness-to-pay and elasticity estimates that are in line with current estimates. I expand this literature by developing an agricultural production model that incorporates substitution between surface and groundwater. My model is concise and allows for new evaluation of surface water policies that cannot be done without incorporating this interaction.

Second, I contribute to an active literature on quantitative estimates of frictions and gains in water marketing (Colby, 1990, Donna & Espin-Sanchez, 2018, Gupta, Hughes, & Wakerman Powell, 2018, Vaux & Howitt, 2018, Rafey, 2023). In particular, two papers on California's water market laid the groundwork for much of my work. Regnacq et al. (2016) apply a trade model to estimate how different trade characteristics affect water trade flows using a similar dataset.[4] Their results align closely with my multinomial logit trade share regression, though this paper goes further by integrating a structural willingness-to-pay model, specific hydrological constraints, dollar-denominated transaction costs, and counterfactual analysis. The most comparable work is Hagerty (2023), which estimates and decomposes transaction costs in California's water market. I contribute by expanding the set of potential traders to agents that may have never traded, incorporating externalities and hydrological constraints, evaluating market impacts on crop choice and groundwater pumping, and considering realistic policy proposals to reduce these transaction costs.

Lastly, I contribute to a growing literature on empirical environmental market design and industrial organization (Russo & Aspelund, 2024, Aronoff & Rafey, 2023, Teytelboym, 2019). Ferguson & Milgrom (2024) highlight that the interaction of transaction costs with externalities is a crucial decision in many externality riddled resource problems. This paper provides an empirical analysis of this relationship in California's water market and motivates further work on optimal property rights frameworks and market design for interdependent resources.

2 Institutional Background

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

2.1 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.[5] In Figure 2(a) I map all rivers in the state with average annual flow over 10 taf and indicate average volumes. There is a structural misallocation of surface water in California where two-thirds of water supply is in the north whereas two-thirds of the demand is in the south (PPIC 2021). Because of this, there has been massive State, Federal, and local investment in canal infrastructure, which I depict in Figure 2(a), endowing California with one of the most advanced and interconnected water distribution systems in the world.

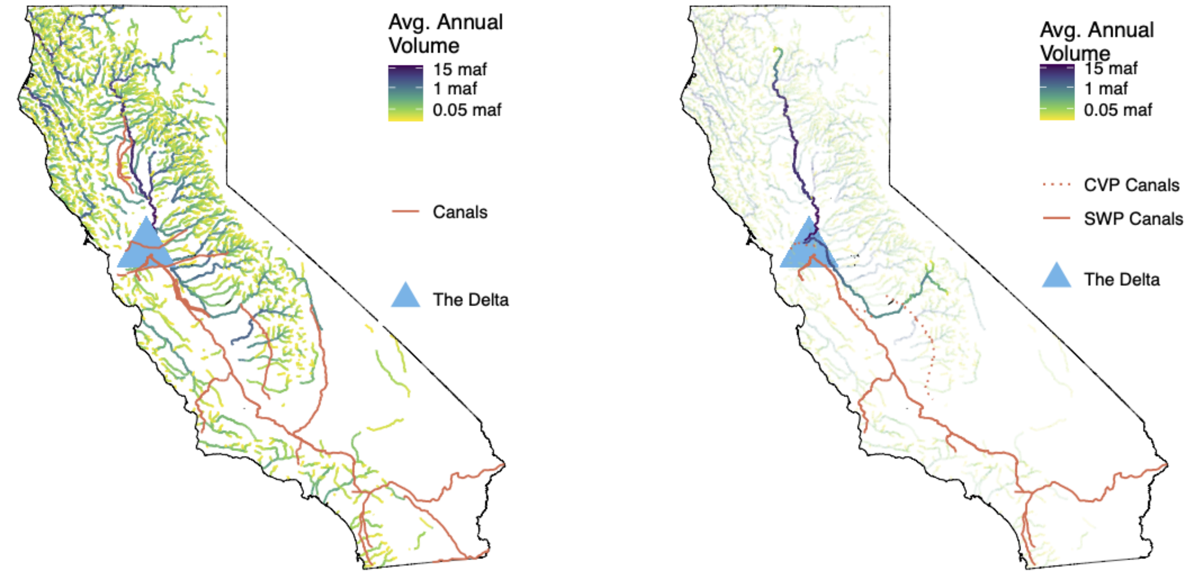
In Figure 2(b), I focus attention on the most important rivers and canals in the system. The Sacramento River, beginning in the north, and San Joaquin River, beginning in the east, meet at the Sacramento-San Joaquin Delta in the middle of the state, just northeast of the San Francisco Bay. There are 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 which is distributed to project

---

[4] I am grateful to Ellen Hanak for sharing this data.

[5] Intrastate supply is supplemented with 4.4 maf of Colorado River imports. Colorado River water is imported from the Colorado River Aqueduct and All-American canals depicted in Figure 2 extending from the most eastern points of the state into Southern California.

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.

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 various other routes (PPIC 2022).

The Delta is the critical nexus in California's water system where abundant flowing surface water supply meets project infrastructure which 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 all urban and agricultural exports.[6] A salinity incident in the Delta would be a catastrophic water policy failure for the environment and for developed supply.

---

[6] There are additional restrictions on project exports to protect fish species that would be killed during the pumping process (PPIC 2022).

Accordingly, there are many constraints and regulations for any water transferred across the Delta.

2.2 Water Rights and Trade

To manage this large, interconnected, and volatile system, California allocates usufructuary property rights to divert surface water directly from rivers.[7][8] Right holders are entitled to a maximum annual quantity in order of seniority - determined by the date in which diversion started. Diversion rights are *incomplete* property rights which do not explicitly clarify all the necessary information for responsible water management. Surface water right specify seniority date, maximum annual volume, maximum rate of diversion, point of diversion, place of use and purpose of use.[9] Rights *do not* explicitly specify the annual quantity users are entitled to or the degree to which the user contributes to downstream supply.

A key feature of surface water management is that a single molecule of water can be diverted by many users before being lost to evaporation or transpiration (Young, 1986). For example, when a farmer diverts water from a stream to irrigate fields of grain, any water not evapotranspirated[10] can enter the watercourse downstream as *return flow* either through runoff or groundwater percolation (Chong & Sunding, 2006). A user downstream may then again divert that same water. While a right holder's annual quantity and contribution to downstream supply is important information for managing the system, these details are not listed ex ante, and instead are implicitly computed at a cost when water transfers are proposed. Irresponsible management of transfers that does not address quantity uncertainty and downstream supply contribution could end up harming other users in the system or contribute to salinity concerns in the Delta.

I present a stylized example to demonstrate how transfers can cause third-party externalities and what steps the State takes to responsibly manage transfers. Figure 3(a), presents a stream that sees 64 thousand acre-feet (taf) of surface water annually. There are three users along the stream. Annually, Alice Irrigation District diverts 48 taf, Charlie City diverts 16 taf, and as water crosses through the Delta into the ocean an additional 16 taf provides vital ecosystem services that mediate saltwater intrusion and sustain endangered fish species.

In total, there are 3 claims totaling 80 taf along the stream which is more than the 64 taf the will flow through the stream. These claims depend on return flow. When Alice applies 48 taf to her crops, she consumes 2/3 through evapotranspiration and 16 taf becomes return flow. Alice's

---

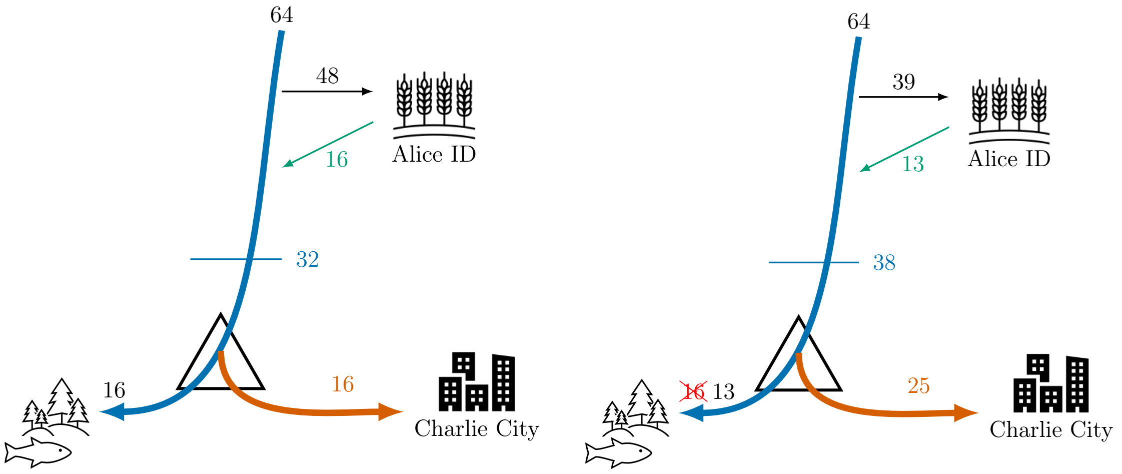
[7] Usufructuary rights are rights to *use* the resource, but not rights to *own*. Since water is a flowing and changing resource, it is much different than land where ownership to physical property is clear and more readily enforceable. No right holder owns particular molecules of water, but instead owns a right to use water according to particular rules (Thompson, Leshy, & Abrams, 2013).

[8] There are both riparian and appropriative property rights in California, along with other unique water right types. For this paper, I mean appropriative property rights when I mention surface water rights as these make up the great majority of water usage in the state and are the only water asset which is has an organized process and clear legal right to transfer (Thompson et al., 2013).

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

[10] Evapotranspiration is the joint process by which water evaporates and is transpirated by plants.

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.

consumptive use varies depending on the type of crops, irrigation technology, and hydrogeology.[11] Charlie City exports water out of the Delta and returns nothing to the originating stream system.[12]

Suppose that Charlie City has a much higher value for water than Alice and they agree to trade 9 taf. In Figure 3(b), I show how this transfer induces negative externalities on the environment. Alice, now only applying 39 taf, returns only 13 taf downstream and Charlie diverts 25 taf. Accounting for Alice and Charlie's consumptive share, there is only 38 taf available in the stream after their uses. The environmental flows are reduced to 13 taf because of the change in Alice's return flow. Without careful management, mutually beneficial trade between Alice and Charlie exerted a negative externality on the environment.[13] Furthermore, as Charlie diverts more surface water he draws additional saltwater into the Delta and could harm endangered fish species. Due to these externalities, California takes the following three steps to manage surface water transfers.

Rights Verification: First, the seller must prove that they have a right to surface water that year and verify the quantity available given drought conditions. Appendix Figure 11 shows a real example of an appropriative right to surface water, which exists on paper but is not digitized or streamlined in a database. The right outlines the maximum quantity of water the user can divert and where it can be used. However, there is not information about how the right adjusts to different years and users are expected to adjust diversion while respecting the rights of other users, which

---

[11] While many of these production technologies and decisions affect consumptive use, most are not contracted on and instead rights coarsely stabilize return flows by restricting water use to the details listed in the right.

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

[13] These externalities can also impact other users along the stream. Typically, right holders will not be aware of reduced supply and so the most downstream return flow dependence will face the burden.

are also un-digitized. In my stylized example, this would amount to Alice ID presenting her right and determining if at least 9 taf are available for transfer. Regulators dedicate much of their time and resources to verifying the quantity endowed by the right for the given year.

Return Flow Measurement: Once the quantity the seller has a right to divert is determined, a return flow measurement is performed to determine the consumptive use of the seller. Sellers are required to present the last five years of crop production and irrigation practices and regulators use agronomic models and measurements to determine the seller's anticipated reduction in consumptive use. The buyer is then restricted to diverting at most the consumptive reduction of the seller, so that return flow externalities are internalized. This would amount to Charlie City diverting 6 taf, since Alice consumes 2/3 of her diversion and plans to leave 9 taf in the stream. Since Charlie can only divert 6 taf, the 38 taf left in the stream is enough to satisfy both Charlie's diversion and the environmental outflow.

Delta Constraints: To avoid saltwater intrusion, protect endangered ecosystems, and ensure the quality of project exports, any transfer that will 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, this means that Charlie City must leave 22% of the 6 taf from Alice as Delta outflow. Ultimately, Charlie City will only be able to export 4.68 taf out of the Delta. If Charlie was not pumping water directly out of the Delta, these carriage water requirements would not be necessary. Currently, California is considering the construction of the Delta Conveyance Project - a pipeline that would avoid the Delta by diverting water from upstream in the Sacramento River and transporting directly to the south of Delta.

Each of these three steps impose transaction costs on transfers, but are important given incomplete information about property rights and existing infrastructure that requires pumping directly out of the Delta. This process, along with others, is cited as a bottleneck in water marketing (Leonard, Costello, & Libecap, 2019a).

> The lengthy and involved process at times required for developing, reviewing, and approving water transfers is a reflection of their uniqueness and the factual complexity and uncertainties that frequently attend them... Because of the interconnectedness of water rights, water uses, and water supply, much of the time spent in the review of water transfers is devoted to determining whether a proposed transfer will adversely affect other water users on the stream.
>
> *"Water Transfer Approval: Assuring Responsible Transfers"*
> *- California Department of Water Resources (2012)*

Existing quantitative analyses of surface water market frictions have identified these three regulatory steps as predictive of reduced trade volumes (Regnacq et al., 2016, Hagerty, 2023). However, the previous literature has not directly controlled for the way these steps reduce tradable quantities. Both the return flow adjustments and carriage water requirements in the Delta act as a wedge between the seller's reduction and the buyer's increased diversion - the potential gains from trade must be large enough to still rationalize trade. I contribute new analysis and results that allows us to differentiate between structural constraints created by these frictions as opposed to the administrative costs associated with management. By distinguishing between these forces, I am able to consider and propose specific policies that will resolve frictions.

Policy variation in when each of these three regulatory steps are required allows me to identify frictions separately. Rights verification is required whenever seller's are trading an underlying right to surface water. When the seller is trading project water, there is no need to perform a rights verification as project water entitlements are clearly listed online and update given drought conditions. Return flow measurement is required for both the trade of rights, and also the export of project water out of project boundaries. Since return flow externalities are only relevant when the underlying property right changes, project water transfers within project do not require return flow measurement. However, any export of project water out of project boundaries will change the place of use of the underlying water light, and a return flow measurement is required. Lastly, any type of water asset may be liable to carriage water requirements when crossing the Delta.

The first two steps, rights verification and return flow measurement, are informational frictions in the market where incomplete property rights require costly verification. I will consider counterfactuals where information is free, through rights adjudication or satellite measurement, and also no-information counterfactuals where conservative lower-bounds on consumptive share are used instead of determining consumptive use specifically for each proposed seller. Delta constraints, on the other hand, are infrastructural frictions that could be resolved with the construction of the Delta conveyance project, which is a counterfactual I will consider.

Of course, there are many other frictions in surface water markets. Many farmers have limited experience with surface water markets and the legal structure around transfers may seem ambiguous.[14] Water is heavy and requires energy to transport great distances. Furthermore, potential trading partners that are far away from each other may be subject to larger search costs. I will address these concerns by incorporating residual frictions and the distance between traders in this market. Another known friction in surface water markets has to do with the political economy of water transfers. Given a fraught history of large transfers (e.g. the *water wars* between Los Angeles and Owens Valley) from agriculture to urban limiting the economic success of the local community that exported the water, there is strong resistance to these kinds of transfers in California. Concern about distributional consequences of trade - pecuniary externalities - are not just a general concern, but California regulators are actually granted the authority to block or modify transfers that unduly harm the exporting local economy. There is limited guidance on how regulators should approach this friction or how strong this sentiment is across different regions, so I do not try to explicitly disentangle what motivates this friction in this paper.[15]

---

[14] Since water rights in California follow the *use it or lose it* principle, where water not put to *beneficial use* may be forfeited, there has been concern that selling water may lead to the loss of right. While this belief may increase frictions, California has asserted many times that water transfers still count as beneficial use and will not lead to a forfeiture of right.

[15] In other work, Ferguson and Kashner (2024) estimate the size of these pecuniary externalities in Australia's

3 Data

I combine land and water use data provided by California's Department of Water Resources (DWR), the State Water Resources Control Board (SWRCB), and the Public Policy Institute of California (PPIC) to create a panel for urban, agricultural, and environmental water uses and trade from 2005-2015.

3.1 Data sources

Crops and Irrigation. The DWR provides a panel of land and water used for 19 different crop categories from 2002-2019 at the Detailed Analysis Unit by County (DAUCO) level. There are 281 DAUCOs in California, which have agricultural production tracked by DWR. For each DAUCO-crop-year, the data include acres grown, applied water per acre, effective rain per acre, and evapotranspiration of applied water per acre. Given DAUCO specific soil, climate, and topology, DWR estimates the quantity of water that must be evapotranspirated to maximize yield for each crop and year. Evapotranspirative needs not met by effective rain make up the quantity that must be met with irrigation. Given irrigation efficiency estimates, the DWR reports how much water must be applied to reach target evapotranspiration levels.

Water Supply and Hydrological Balance. To meet regulatory obligations in the California Water Code, DWR must release the California Water Plan which frames and informs water policy. To carry out the analysis, the DWR builds large-scale hydrological models to study counterfactual water policies and climactic scenarios. The DWR Water Balance data provides DAUCO-year-use level estimates of many key variables output by their hydrological models. The three uses are: urban, agricultural, and environmental. The data breakdown sources of water use into water rights, project water, groundwater, and return flow dependence. Environmental water use is broken down between wild and scenic rivers, in-stream flow requirements, and Delta outflow requirements. I will use this data to estimate sources of water supply and construct a network of return flow externalities.

Hydrological Network. The U.S. EPA Office of Water manages the National Hydrography Dataset (NHD) that provides information about streamflow and hydrological connectivity across the entire United States. Using version NHDPlusV2 for California, I construct a model of the river network between each DAUCO. While the NHD dataset includes microdata on natural river interconnectedness, artificial infrastructure like canals or aqueducts are not as clear. I compile three different datasets from state and federal sources that include cross-regional canals and aqueducts. Additionally, I supplement the artificial infrastructure using urban water district and irrigation district shapefiles which have intra-district infrastructure. I combine cross-regional canal infrastructure with intra-district connectivity to create the network of conveyance between DAUCOs. In Appendix Sec-

---

Murray-Darling Basin and consider market designs that can compensate exporting communities so that Pareto gains are made.

tion D, I detail how these networks are constructed.

Groundwater Basins and Pumping. The DWR releases an unbalanced panel of measurements from 43,659 groundwater pumps in the state covering 515 basins from 1888-2023. I observe the depth to groundwater and the surface area of the basin. For some basins I observe groundwater depth at in monthly intervals and for other I only see yearly data. Appendix Section E discusses how I clean the data to create a panel of groundwater levels at the DAUCO-year level from 2002-2019. To gather electricity prices and groundwater pumping energy-need data I scrape results from a California Energy Commission report on regional groundwater energy-use. The report allows me to create a panel from 2005-2015 of agricultural energy prices and energy use at the hyrdrologic regional level.

Urban Water Utilities. From 2016-2022, residential water utilities reported operations data to the DWR as a part of an audit with the American Water Works Association (AWWA). The panel includes for 238 utilities, a breakdown of water sources, total quantity provided, number of households provided, average unit price for water, variable cost, and total cost of operations. This data forms the backbone of my urban water demand estimation.

Surface Water Transfers. The Public Policy Institute of California (PPIC) manages a panel from 1982-2019 of water transfers in California. Since there does not exist a single agency or dataset that tracks all types of water transfers in California, the PPIC compiles data from various sources to create the most comprehensive and detailed dataset available. Sources include the State Water Project (SWP), Klamath Project, Central Valley Project (CVP), Colorado River project, National Environmental Policy Act (NEPA) documentation, State Water Resources Control Board (SWRCB) Temporary Transfers, major water districts, and individually investigated transfers. The panel identifies buyers and sellers, the type of water being transferred, quantity transferred, Delta carriage water adjustments, whether the trading agents are agricultural or urban, and the length of transfers (if long-term).

Other Supplementary Data. Some analysis requires ancillary data to describe characteristics of particular agents. I collect tract-level median income from Census data, household lot size from Infutor, and precipidation data from PRISM. Each is aggregated either to the DAUCO or utility level using geographic shapefiles provided by DWR or from Nick Hagerty's water rights database (Hagerty, 2023). I also utilitze Hagerty's DAUCO-aggregated panel of project allocations.

3.2 Water Supply and Uses

Surface water availability in California varies considerably across years. Table 1 shows the breakdown of surface water uses (agricultural, urban, and environmental) across years. On average, half of total surface water runoff is put to environmental uses. This includes in-stream flow requirements, managed wetlands, wild and scenic rivers, and required Delta outflow. Each particular use helps

Table 1: California Water Use and Supply Summary

	Dry			Normal			Wet		
	p10	p50	p90	p10	p50	p90	p10	p50	p90
Agriculture									
Farmland (Thousand Acres)	27.4	142	476	27.5	142	476	27.1	142	476
Share Fallowed	0.03	0.16	0.31	0.02	0.11	0.3	0.03	0.13	0.32
Total Irrigation (TAF)	72.2	454	1250	68.5	418	1190	71.8	413	1210
AF/Acre	2.68	3.57	4.88	2.5	3.31	4.6	2.64	3.51	4.78
Consumptive Share	0.73	0.84	0.91	0.67	0.77	0.89	0.65	0.7	0.76
Surface Water (TAF)	6.4	116	499	10.6	216	736	15	228	798
SW Share Project	0	0.09	1	0	0.09	0.95	0	0.05	0.97
Groundwater (TAF)	0	166	905	0	95.8	496	0	84.4	431
GW Depth (ft)	22.6	82.4	281	16.2	66.1	235	11.8	56.3	148
Return Flow Supply (TAF)	0	0.2	34.1	0	0.8	55.9	0	1.65	64.3
Return Flow Demand (TAF)	0	0	23.8	0	0	40.4	0	0.1	31.4
Urban									
AF/Service Connection	0.47	0.61	0.91	0.48	0.63	0.94	0.55	0.71	1.15
Surface Water (TAF)	0.94	3.4	6.2	0.66	3.38	7.4	0.84	3.74	7.04
SW Share Project	0.07	0.57	0.86	0.27	0.53	0.88	0.36	0.59	0.84
Groundwater (TAF)	1.21	6.96	35.1	2.33	8	38	3.37	7.98	47.5
Return Flow Supply (TAF)	0	0	5.19	0	0	6.73	0	0	7.13
Return Flow Demand (TAF)	0	0	0	0	0	0	0	0	0
Environment									
Instream Flow (Total TAF)	232	389	504	274	549	1000	181	380	791
Instream Flow (RF TAF)	50.6	68.9	79.6	71.2	94	165	133	155	167
Wild and Scenic (Total TAF)	13	16	24.4	0	42	174	0	54.7	700
Wild and Scenic (RF TAF)	1.93	2.92	3.55	2.24	3.14	11.8	7.25	9.46	11.5
Managed Wetlands (Total TAF)	98.9	149	160	125	145	177	88.5	152	179
Managed Wetlands (RF TAF)	63.4	70.3	79.4	62.9	91.6	103	64.2	75.3	81.2
Delta Outflow (Total TAF)	3420	3750	4250	3210	4460	5510	1810	2930	4640
Delta Outflow (RF TAF)	869	1190	1500	1280	1810	2120	1870	1930	1960

Notes: Table reports summary statistics about surface water trade in California from 2005-2015. Years are considered *Normal* within the inter-quartile range of total statewide surface water volume, with *Dry* and *Wet* below and above this range. Within each type of year, the 10th, median, and 90th percentiles across units for the listed statistic are reported. Agricultural are DAUCOs, Urban units are water utilities, and Environmental units are years.

maintain natural ecosystems, sustain endangered species, and preserve protected rivers or areas. Beyond these explicitly environmental uses, both in-stream flow and Delta outflow requirements are necessary to preserve both agricultural and urban supply from degradation. Without sufficient in-stream flows or Delta outflow, the remaining half of surface water uses could be rendered unusable. As total surface water supplies decrease, environmental flows take the largest cut. The remaining half is split about 4:1 between agricultural and municipal uses.

I categorize *Wet*, *Dry*, and *Normal* years by the upper quartile, lower quartile, and inter-quartile of annual statewide surface water availability. In Table 1 I report more detailed water use and supply statistics at the level of the respective units of analysis. Agricultural, urban, and environmental units are at the DAUCO, utiliy, and statewide level, respectively. Within each use and type of water year (Dry, Normal, or Wet) I report the 10th, median, and 90th percentile unit's statistic. There are 281 agricultural DAUCO units, 238 urban utilities, and 1 statewide environmental unit which I observe from 2002 to 2019.[16]

3.2.1 Agricultural Use and Supply

The median DAUCO has 142,000 acres of potential farmland and irrigates with around 425,000 af. In Dry years, the median DAUCO leaves 16% of this land fallow. While surface water is more scarce in Dry years, fallowing statistics seem to be relatively constant. This is because there is substantial substitution to groundwater pumping when surface water supplies are scarce. From Wet to Dry years, median surface water availability decreases by 112 taf and median groundwater pumping increases by 81.6 taf.

Groundwater pumping in California has been largely unregulated and has acted as the outside option for water starved farmers. The cost of groundwater pumping to the farmer depends critically on the depth to groundwater - how far water must be pumped. Dry years see the highest depths and there is substantial variation across DAUCOs. In Figure 4, I map average surface water use (in Panel A) and groundwater depth (in Panel B) across DAUCOs. Notably, surface water resources are found largely north of the Delta, and south of the Delta groundwater is pumped at the highest depths. Since groundwater cost is directly related to depth, this descriptive evidence already provides suggestive evidence of gains from trade between farmers with surface water and farmers that must pay more to pump groundwater farther.

Return flow supply and dependence is clustered around a smaller set of DAUCOs. In all levels of scarcity, the median DAUCO supplies/depends on little return flow. However, 90th percentile DAUCOs in Dry and Wet years provide 34.1 taf and 64.3 taf respectively. For perspective, that means that nearly 30 DAUCOs each return at least half a million people's worth of water to the system in Wet years. Between a half and two-thirds of this return flow is re-used by farmers in other DAUCOs.

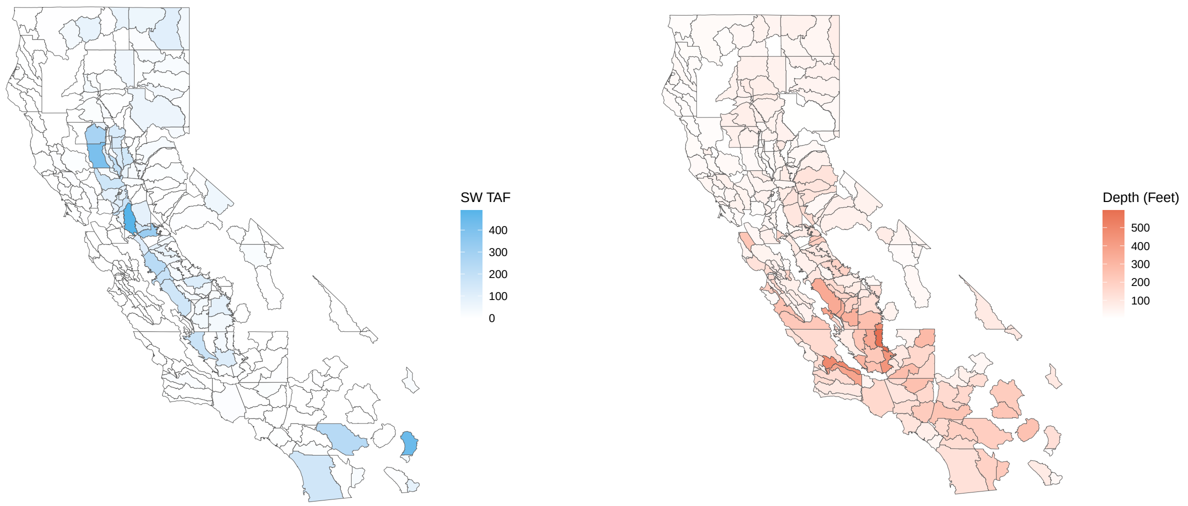
3.2.2 Urban Use and Supply

The median utility has 43,167 service connections and supplies 0.63 af in a Normal year. This median water supply per service connections varies between 0.61 and 0.71 from Dry to Wet years. The impact of surface water scarcity on urban utilities creates more variability as senior water rights are largely held by agricultural users and urban utilities often overly adjudicated groundwater basins which are more regulated and cannot act as an always available outside option. Per connection supply and the composition of sources from surface water, project water, and groundwater vary widely between utilities. In particular, project water dependence is much greater amongst utilities than agriculture. The median utility receives half of their supply from projects, compared to only 10% amongst DAUCO agricultural use. On the other hand, return flow contributions and

---

[16] The AWWA utility audit data only includes years 2016-2022. I combine this data with urban supply data from the DWR water balance data to create a panel from 2002 to 2019.

Figure 4: DAUCO Agricultural Surface Water Use and Groundwater Depth



(a) Surface Water Use (b) Depth to Groundwater

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

dependence are much less prevalent amongst utilities.[17]

3.2.3 Environmental Use and Supply

In a median year, statewide instream flow, wild and scenic, managed wetlands, and Delta outflow requirements are 549 taf, 42 taf, 145 taf, and 4,460 taf respectively. Delta outflow needs are more than 5 times the other uses combined. Furthermore, the Delta's needs persist in Dry years and are especially dependent on return flows. On average, over 40% of environmental water use is sustained by agricultural and urban return flows. When water users engage in trade, this dependence must be evaluated to insure there is no harm.

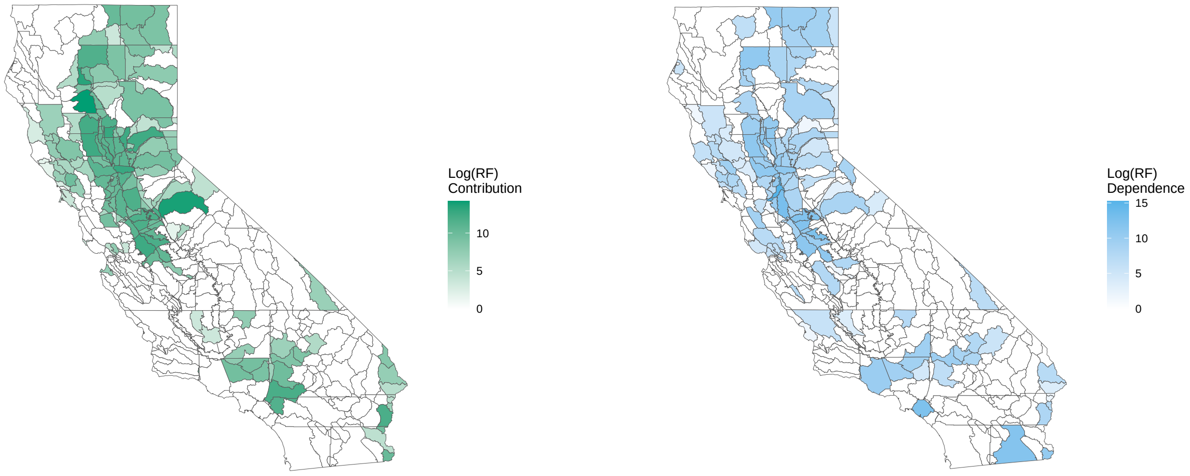
3.2.4 Return flow dependence and externalities

Understanding the nature of return flow dependence is crucial to responsibly managing water resources (Anderson, 2012). In California's case, since return flow dependence is largely concentrated in the Delta, mistakes in return flow management could destroy protected habitats, kill endangered species, or render statewide water supplies to saline for use. Unfortunately, detailed information on how specific changes in water use will return flow availability for third-parties is scarce. A key contribution of this paper is estimating and incorporating the details of this return flow dependence into the evaluation of different water market designs.

---

[17] However, recall that "environmental" dependence in the Delta sustains project supply to urban users.

Figure 5: Return Flow Contributions and Dependence



(a) Contributions to Return Flow (b) Dependence on Return Flow

Notes: Panels (a) and (b) depict the logged average return flow contributions and dependence of each DAUCO from 2005-2015.

As detailed in Appendix Section E, I estimate a return flow network between DAUCO-uses from aggregate data on DAUCO water dependence provided in the DWR water balance data. Appendix Figure 12, depicts the directed network of return flow dependence between DAUCOs in California. Most of the complicated interconnectedness is concentrated in and around the Delta. In Figure 5 I map average agricultural and urban return flow contributions and total return flow dependence across the state. Most of the contributions and dependence cluster along the Sacramento and San Joaquin Rivers, which flow into the Delta.

This network will enables counterfactuals that tradeoff costly return flow monitoring with reallocative flexibility and potential return flow externalites. To my knowledge, this is the first economics paper to take return flow contributions and dependence seriously as a constraint for water market design.

3.2.5 Water Market Activity

Using the panel of water transfers provided by the PPIC, I depict trade volumes relative to total surface water volume in Figure 1(b) and report in Table 2 summary statistics trades across different degrees of scarcity and then report the shares of trade volume that are a part of water transfers with particular characteristics. The kinds of variation in trade activity across features of transfers will be important for studying the magnitudes of particular frictions and which kinds of redesign will improve market activity.

The total volume and count of water transfers hovers between a quarter and three quarters of a million acre-feet across years. This total quantity of trade does not seem to correlate with the severity of drought. In a median Normal year, 438,000 af is traded which is more than both median Dry and Wet years. During Dry years there is more incentive to trade, but less water to go around and in Wet years there is more water to go around, but less incentive to trade.

Table 2: Water Market Summary

	Dry			Normal			Wet		
	p10	p50	p90	p10	p50	p90	p10	p50	p90
Summary									
Total transfer volume (TAF)	265	385	479	380	438	660	276	325	524
Transfer count	95.5	131	232	119	185	249	136	164	203
Share of transfer volume									
Right is traded	0.108	0.155	0.178	0.015	0.041	0.189	0.039	0.063	0.142
Real water determination	0.151	0.205	0.239	0.027	0.065	0.266	0.043	0.078	0.147
Within CVP	0.454	0.579	0.675	0.488	0.692	0.825	0.798	0.853	0.903
Within SWP	0.103	0.145	0.251	0.116	0.2	0.262	0.023	0.038	0.048
Within hydrologic region	0.294	0.36	0.569	0.425	0.53	0.658	0.551	0.647	0.693
Crossed Delta	0.081	0.416	0.603	0.009	0.171	0.23	0.003	0.011	0.016
Within agriculture	0.783	0.806	0.825	0.511	0.824	0.902	0.839	0.854	0.935
Agriculture to urban	0.033	0.055	0.083	0.014	0.052	0.413	0.044	0.095	0.113
Urban to agriculture	0.042	0.087	0.111	0.027	0.066	0.095	0.009	0.025	0.031
Within urban	0.018	0.057	0.102	0	0.025	0.062	0.008	0.017	0.028

Notes: Table reports summary statistics about surface water trade in California from 2005-2015. Years are considered *Normal* within the inter-quartile range of total statewide surface water volume, with *Dry* and *Wet* below and above this range. Within each type of year, the 10th, median, and 90th percentiles across DAUCOs for the listed statistic are reported.

The breakdown of characteristics of trade shows that the majority of trades in every years are farmer-to-farmer and within the Central Valley Project. Any trade involving a city, either as a buyer or seller, is much less likely. In a 90th percentile Normal year, the largest share of trade from farmers to cities at 41.3% of trade volume. This is surprising given that that large gains exist between agricultural and urban users.

Trades crossing the Delta are especially unlikely in wetter years but in Dry years can make up over half of all trade volume. Recall that groundwater depth, which is essentially pumping cost up to a scaling, is much deeper south of the Delta with most surface water flowing north of the Delta. Only in Dry years do transfers adjust for this kind of misallocation. Real water determinations are similarly more likely in drier years, but do not show as stark a pattern.

4 Reduced Form Analysis

In this section, I provide reduced form evidence of agricultural substitution to groundwater and of surface water market trade frictions to motivate a structural model of willingness-to-pay for surface water and a water market for bilateral trades under transaction costs.

4.1 Groundwater Substitution

Farmers could respond to surface water scarcity by fallowing land, substituting to groundwater pumping, or by switching crops. In Section 5 I will incorporate all three decisions in a model of agricultural production. Before building up a structural model, I first establish some descriptive statistics on the elasticity of fallowing and groundwater pumping to surface water availability. These elasticities both inform how farmers value surface water and how the agricultural economy may change in response to alternative surface water allocation mechanisms.

Each DAUCO is endowed with surface water SW_{it} that adjusts each year according to hydrological conditions, the seniority of property rights owned within the DAUCO, and the set of contracts with project water. To understand how the quantity of groundwater pumping varies with surface water availability, I estimate the following regression:

$$GW_{it} = \alpha SW_{it} + \beta \mathbf{X}_{it} + \theta_i + \xi_t + \varepsilon_{it}. \tag{1}$$

The parameter of interest is α, representing the marginal response to an additional unit of surface water. I include controls for effective rain (the amount of precipitation usable for agricultural production) and groundwater depth along with both DAUCO and year fixed effects. I report results in Table 3. For each additional acre-foot of surface water, farmers substitute to pumping 0.848 acre-feet of groundwater.

This substitution pattern aligns with the summary statistics in Table 1 on statewide agricultural surface water and groundwater use across different drought scenarios. It makes sense that groundwater is not a perfect substitute since surface water endowments are essentially free whereas groundwater must be pumped at a cost. The elasticity of groundwater pumping to surface water is equivalent with respect to effective rain - the amount of rain that can effectively offset irrigation needs.

Two key takeaways from this analysis motivate the model in Section 5. First, groundwater substitution is a key margin of adjustment for farmers. Second, surface water availability affects the decision to pump in the same way precipitation does.

4.2 Decomposing Frictions to Surface Water Transfers

The set of hydrological and regulatory frictions depends delicately on the locations and identities of potential surface water buyers and sellers. To motivate decomposing the relative magnitude of different frictions, I leverage panel data on surface water transfers to analyze how surface water

Table 3: 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 1 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.

endowed in particular markets ends up being traded to different markets or remaining within the originating market. This section analyzes the kinds of water market trade volume variation discussed in Table 2.

Define a market as a region-water class-year. There are 8 hydrologic regions that trade from 2005-2015. There are three classes of surface water: Rights, SWP, and CVP. SWP and CVP project water is managed by the state and federal government respectively and affords administrative benefits to trade within projects. Surface water rights greatly outnumber project water, but are subject to additional frictions.

The underlying property right to water could be transferred, or alternatively, project water can be transferred within the project. For each market, I compute the total amount of endowed surface water and the total volume traded to each other market. Let s_{odt} be the share of water traded from market o to market d in year t.

For each water right in a given year, the owner can choose to keep it or sell it. Depending on the seller's market and the buyer's market, the transfer will be subject to different transaction costs. For example, infrastructural frictions when crossing the Delta depend on the locations of buyers and sellers. In particular, three different categories of transfers allow us to separately estimate the contribution of rights verification and return flow measurement to trade frictions. Recall from Section 2.2 how transfers of rights are subject to right verification costs while project water is not. Since any transfer of rights or transfer of project water out of project boundaries requires a change in place of use, both these kinds of transfers require return flow measurement. Importantly, project exports require return flow measurement but not right verification. Lastly, transfers of project water within project boundaries require neither rights verification nor return flow measurement. This policy variation in informational frictions across different water assets enables the decomposition and contribution of each to reduced trade.

I estimate the following regression:

$$\log(s_{odt}) - \log(s_{oot}) = \beta X_{odt} + \theta_{ot} + \eta_d + \varepsilon_{odt} \tag{2}$$

where X_{odt} includes the difference in median marginal gains from trade between origin and destination regions[18], dummy variables for the water uses of the seller and buyer, if a right is being sold, if project water is being exported, if the transfer crosses the Delta, and the distance in miles between traders. I include seller's market and buyer hydrologic region fixed effects. In the second specification, I include willingness-to-pay estimates from my agricultural production and urban demand models.

Table 4: 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 5.1 and 5.2

In Table 4, I report the results from estimating the regression in Equation 2. I see evidence of informational frictions from the negative coefficients on rights and project exports. The magnitude of these coefficients suggests that return flow measurement costs, which are required in both cases, are less than a third of the magnitude of rights verification. The infrastructural frictions associated with crossing the Delta are equally indicative of reduced trade as return flow measurements costs.

---

[18] I use estimates from my agricultural and urban willingness-to-pay models in Sections 5 and 6 to compute marginal gains.

These three sources of transactions costs are large relative to other characteristics like distance.

In the second column, I include the average gap in marginal willingness-to-pay for surface water between markets, which I estimate in Section 5. Marginal gains between origin and destination markets are highly predictive of trade. Controlling for potential gains reduces the magnitude of project export and Delta frictions, but most notably triples the coefficient on transfers from agricultural to cities. As suggested by earlier evidence and estimated in my structural models, there are large potential gains between farmers and cities that do not realize. While column (1) highlighted informational and infrastructural as prevailing explanations, other frictions between farmers and cities may play a large role.

4.3 Motivating a Model

While the evidence in Table 4 highlights trade frictions, it does not provide dollar denominated estimates of transactions costs nor a clear framework to evaluate counterfactual designs. Furthermore, many of the frictions are not simply administrative or bargaining costs, but structural frictions accompanied with physical restrictions on trade that are necessary to avoid third-party externalities.

For example, transfers that cross the Delta must also provide carriage water as outflow, reducing how much water a buyer can actually receive. Transfers requiring return flow measurement are limited by the consumptive use of the seller. Hydrologic connectivity or conveyance infrastructure must exist between trading partners. Regressing market activity on each of these frictions may reveal the shadow cost of such friction, but will not decompose the friction into the physical constraint and the administrative overhead. Are return flow measurements costly because of the bureaucratic burden or is constraining buyers to the consumptive reduction of the seller creating the friction? Is California managing the Delta as efficiently as possible given critical constraints on saltwater intrusion or can alternative management free up trade?

To answer these kinds of questions, I need to incorporate hydrological constraints and the status quo restrictions on trade that satisfy them. Since these constraints and restrictions depend on specific details of buyers and sellers, I also need more granular information about willingness-to-pay. The regression evidence affirmed that properly adjusting for willingness-to-pay can change which frictions seem more important. Furthermore, the transaction-level, joint distribution of physical/externality constraints, transaction costs, and gains from trade will determine the value of different policy interventions.

5 Model of surface water market with transaction costs

In this section, I formulate models of agricultural willingness-to-pay, urban willingness-to-pay, and bilateral trade under transaction costs. The agricultural and urban models will dictate how agents behave in bilateral trade model.

5.1 Agricultural demand

5.1.1 Crop Production and Groundwater Pumping

Before season t, farmers are endowed with surface water SW^e_{it} according to their rights and project contracts. Before making production decisions, farmers can trade surface water resulting in access to SW_{it} acre-feet of surface water. Once final surface water resources are known, farmer i decides for each acre a of land L_i which crop $k_a \in K$ to grow. Production is Leontief in land and water so that for each acre of crop k, the farmer must apply aw_{ikt} of water. Applied water needs depend on farmer-year specific details like humidity, precipitation, temperature, and land quality. Farmers combine surface water and groundwater to meet total applied water needs where groundwater can be pumped at convex cost $C(GW_{it})$.

Groundwater cost depends on the price P^e_{it} of electricity per kWh and the depth to groundwater H_{it}. Each foot of pumping requires ρ_i kWh of electricity which varies depending on pumping technology and basin-specific geology (Timmins, 2002). For each acre-foot of water pumped, the water table is decreasing and so the depth to groundwater increases by γ_i. Endogenous pumping-height implies convex groundwater cost in the total quantity of water pumped (Timmins 2002). These properties yield the following cost of groundwater:

$$\begin{aligned} C_{it}(GW_{it}) &= \int_0^{GW_{it}} P^e_{it}\rho_i(H_{it} + \gamma_i x)dx && (3) \\ &= P^e_{it}\rho_i(H_{it}GW_{it} + \frac{\gamma_i}{2}GW^2_{it}). && (4) \end{aligned}$$

For each acre, farmers pay non-water marginal costs c_{ikt} and receive revenue R_{ikt} for their yield. Marginal costs cover all other inputs like seeds, fertilizers, labor, which I assume have constant marginal cost and are chosen optimally by the farmer. Additionally, I assume agricultural commodities markets are competitive and revenue is taken as given. I define farmer-crop-year non-water profit $\pi_{ikt} = R_{ikt} - c_{ikt}$. The farmer's crop decisions depend on this non-water profit parameter, but do not depend on revenue and non-water marginal cost separately. I model heterogeneity in non-water profit with identically and independently distributed acre-level Type 1 extreme value shocks ε_{akt} scaled by parameter ν.

Altogether, the farmer makes crop choices for each acre that maximizes total profit:

$$\Pi^*_{it} = \arg\max_{k_a} \sum_a (\pi_{ik_a t} + \nu\varepsilon_{ak_a t}) - C_{it}(\sum_a aw_{ik_a t} - SW_{it}). \tag{5}$$

This combinatorial problem is not analytically convenient. As detailed in Appendix Section A, relaxing global profit maximization and instead assuming that farmers are making locally optimal choices where any acre-level deviation in crop choice would decrease profit yields a smooth objective function. Under this assumption and when aw_{ikt} is small relative to GW_{it}, the farmer's acre-level crop choice problem is approximated with a multinomial crop share problem where farmers allocate shares s_{ikt} of their land to each crop:

$$\Pi^*_{it} = \arg\max_{s_{ikt}} \sum_k L_i s_{ikt} \pi_{ikt} - C_{it}(\sum_k L_i s_{ikt} aw_{ikt} - SW_{it}) - \frac{\nu}{L_i}(\sum_k s_{ikt} \ln s_{ikt}). \tag{6}$$

This maximization yields an analytically tractable description of optimal crop choices that should resemble results from standard multinomial logit models. Letting the outside option $k = 0$ represent a farmer's choice to fallow, the optimal crop shares equate total marginal crop profit with the scaled log ratio of crop share to fallowing share.

$$\nu(\ln s_{ikt} - \ln s_{i0t}) = \pi_{ikt} - aw_{ikt} P^e_{it} \rho_i (H_{it} + \gamma_i(\sum_k L_i s_{ikt} aw_{ikt} - SW_{it})). \tag{7}$$

Varying the optimal profit function with surface water SW_{it} pins down the farmer's value for surface water:

$$V_{it}(SW) = \Pi^*_{it}(SW). \tag{8}$$

5.1.2 Notes on agricultural model

First, my model shares a similar final estimating equation to the management cost function in Carpentier & Letort (2014). To explain crop-diversification in their setting they include an entropy cost to crop share choice that they argue represents the impact of quasi-fixed capital, risk, and heterogeneous irrigation timing. One contribution in this paper is demonstrating that their model approximates one with logit shocks at a granular level of production.

Second, the marginal cost of pumping groundwater plays a focal role in this model of agricultural production. The marginal value of surface water is exactly the marginal cost of groundwater. I view incorporating groundwater substitution into my agricultural model as a key innovation and contribution of this paper. Prior research on water marketing in California has either kept surface water or groundwater resources fixed in their analysis of crop choice (Burlig et al., 2024, Hagerty, 2023, Regnacq et al., 2016). First, in speaking with farmers cooperatives and scientists at the DWR, I found that groundwater pumping is a key margin of substitution that accurately describes the farmer's production choices and informs where surface water is valuable. Second, while not a feature in this paper, the surface-groundwater hydrological nexus has its own set of externalities on supply and on the environment. For example, over-pumping can lead to land subsidence, collapsing canal infrastructure, poisoned water supply, and can deplete flowing surface water supply. Any significant change to surface water management is sure to impact groundwater pumping choices which, if not incorporated into the new surface water policies, may yield bad side effects for the system as a whole. Unfortunately, the surface-groundwater nexus is not well understood hydrologically, let alone economically, and I view this as an important direction for future market design work as information becomes more available.

5.2 Urban demand

I assume that each utility i maximizes surplus net of water production costs. Urban consumers' demand responds to the average cost per acre-foot P_{it} (Ito, 2014). Demand depends on characteristics of the utilities' consumers including: rainfall, household income, lot size, and population. I model the total quantity of water demanded Q_{it} by:

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

Integrating the demand curve I compute the consumer surplus from a given quantity of water X. However, this represents the willingness-to-pay of the consumer and not of the utility. The utility must pay a marginal production cost per unit of water that includes transportation, treatment, and maintenance. I assume that the utility faces a marginal water production cost of ϕ_i that represents all services other than sourcing the water. This implies the following consumer surplus function adjusted for utility production costs that traces out the utility's value for surface water on the open market.

$$V_{it}(X) = \int_0^X \frac{1}{\eta}\Big(\ln q - \beta \mathbf{X}_{it} - \theta_i - \xi_t \Big) - \phi_{it} \, dq. \tag{10}$$

5.3 Bilateral Trade and Transaction Costs

In a bilateral trade each trader has a value $V_i(w)$ for water w. Agricultural and urban values for water are as described in Equations 8 and 10. Trades are subject to a constant per-unit transaction cost $\tau_{sbt}(\theta)$ that depends on the seller-buyer-year and transaction cost parameters θ. Before trading, sellers and buyers have W_s and W_b water. The total gain from trading w units is:

$$G_{sbt}(w, W_s, W_b, \theta) = \Big(V_{st}\big(W_s - w\big) - V_{st}\big(W_s\big) \Big) + \Big(V_{bt}\big(W_b + \alpha(s,b)w\big) - V_{bt}\big(W_b\big) \Big) - \tau_{sbt}(\theta) w$$

The adjustment function $\alpha(s,b)$ is one of the most important features of this model that has been missing in the literature. This function explicitly incorporates how hydrological constraints map to physical trade frictions in the water market. Recall the stylized example in Figure 3. Charlie City bought 9 taf from Alice, but could only increase his diversion by 4.68 taf. According to return flow and Delta management regimes, when Alice reduced her diversion by $w = 9$ taf, Charlie City could only increase his diversion by the Alice's consumptive use net carriage water for the Delta, $\alpha(s,b)w = (1 - 0.22) \times 0.67 \times 9$. By including this tradable water adjustment, I separate transaction costs from the trade constraints that maintain hydrological feasibility or avoid externalities.

Furthermore, this function generalizes a series of potential policy proposals to manage these externalities. For example, the current CA policy regime (when not crossing the Delta) is $\alpha_{CA}(s,b) = \alpha_s$, where α_s is the consumptive share of the seller. Return flow measurement costs are required to determine α_s. I consider policies that set $\alpha_{fix}(s,b) = \alpha$ to a fixed share regardless of the trading partners identities so that no cost must be paid to adjudicate the trade.[19] I consider removing

---

[19] In many cases, the optimal adjustment would be $\alpha_{fix}(s,b) = \alpha_s / \alpha_b$ which translates to trading net water use.

adjustments and evaluate the trade-off between the magnitude of externalities and the gains. I use this function to estimate market gains from new infrastructure that does not require carriage water for the Delta.

Given trade adjustments $\alpha(s,b)$, transaction costs τ_{sbt}, and gains from trade, the joint surplus maximizing trade between a buyer and seller is:

$$w^*_{sbt}(W_s, W_b, \theta) = \arg\max_{w} G_{sbt}(w, W_s, W_b, \theta) \tag{11}$$

6 Estimation

The key objects to estimate are agricultural values in Equation 8, the urban values in Equation 10, and the transaction cost parameters θ in Equation 15. Both the farmer and urban models make use of exogenous variation in surface water supplies to instrument for groundwater and utility prices, respectively. I estimate transaction costs by matching different trade volumes with simulated method of moments.

6.1 Estimation of pumping cost and crop parameters

I do not have farmer-level data and instead treat DAUCOs as the decision maker i.[20] I observe, $L_i, P_{rkt}, aw_{ikt}, P^e_{it}, H_{it}$, and s_{ikt}, leaving γ_i, ρ_i, π_{ikt}, and ν for estimation.

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

$$\hat{\gamma} = \arg\min_{\gamma} \left(\overline{\gamma} - \sum_{it} GW_{it} \cdot \frac{\gamma}{\text{BasinSurfaceArea}_i}\right)^2 \tag{12}$$

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.

$$\hat{\rho}_r = \arg\min_{\rho_r} \sum_h \left(E_{rt} - \rho_r \sum_{i\in r} \left(H_{it} GW_{it} + \frac{\gamma_i}{2} GW^2_{it}\right)\right)^2 \tag{13}$$

With $\hat{\rho}_r$, the local optimality condition in Equation (7) enables computing $\hat{\pi}_{ikt}(\nu)$ by:

$$\hat{\pi}_{ikt}(\nu) = \nu(\ln s_{ikt} - \ln s_{i0t}) + aw_{ikt} P^e_{it} \hat{\rho}_{r(i)}(H_{it} + \gamma_i(\sum_k L_i s_{ikt} aw_{ikt} - SW_{it})) \tag{14}$$

While this may be optimal, this policy cannot be applied in all hydrological scenarios, in particular when buyers do not return water in the same place as sellers. I ultimately find that the choice of $\alpha(s,b)$ does not significantly impact trade and so do not introduce the extra complexity of this more sophisticated policy proposal.

[20] Under the assumption that farmers within a DAUCO share non-water profit parameter π_{ikt}, accurately anticipate the pumping needs of other farmers, and do not strategically time groundwater pumping, my model is equivalent to a model with many farmers making their own (locally) optimal crop choices.

For any choice of ν, I can match crop shares and groundwater pumping with some set of $\hat{\pi}_{ikt}(\nu)$. Without further structure, non-water profit parameters could capture variation in surface water water availability. For example, in wet years, farmers may grow much more rice and the model will attempt to rationalize this with higher non-water profit for rice. Since surface water endowments are exogenous across years within DAUCO, I require that within-DAUCO variation in surface water availability is not correlated with non-water profit. Define $\overline{\pi}_{ik}(\nu) = \frac{1}{T}\sum_t \hat{\pi}_{ikt}(\nu)$ and $\overline{SW}_i = \frac{1}{T}\sum_t SW_{it}$. I choose $\hat{\nu}$ to minimize the following condition on the correlation between non-water profit parameters and surface water.[21] Satisfying this condition is using surface water availability as an instrument for groundwater pumping costs.

$$\hat{\nu} = \arg\min_{\nu} \sum_{i,k} \Big(\big(\hat{\pi}_{ikt}(\nu) - \overline{\pi}_{ik}(\nu)\big) \cdot \big(SW_{it} - \overline{SW}_i\big) \Big).$$

In Table 5 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}.[22]

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 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 Appendix Figure 14 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 12 cents per kWh. Pumping efficiency estimates vary between 1.4 and 3.8 kWh/af/ft. [23] 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.[24]

6.2 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.

There is a complex supply chain between water utilities and wholesalers that ultimately determines supply. While many utilities have their own property rights or project contracts to surface water, a majority of supply is determined according to the wholesaler market. Utilities with their own secure right are guaranteed a level of supply whereas utilities without their own water re-

---

[21] This is equivalent to regressing the log difference in shares on marginal groundwater costs and DAUCO-crop fixed effects and instrumenting for groundwater costs with surface water supplies. In Appendix Table 12 I report the equivalent instrumental variables regression estimates.

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

[23] In Appendix Figure 15 I map the geographic variation in pumping efficiency.

[24] 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.

Table 5: 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.

sources 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.[25]

In Table 6 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.

---

[25] While rainy years could influence demand, I control for that in my regression and note that the rain that determines surface water supply often falls in the mountains as snow and is unrelated to local rain relevant for landscaping.

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 5.2 to compute residential willingness-to-pay for surface water on the open market.

Table 6: 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
Year-HydroRegion fixed effects	✓	✓	✓
UtilityID fixed effects	✓	✓	✓

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. In Appendix Figures 19 and 19 I residualize DAUCO and utility willingness-to-pay by year and year-region which reduces potential gains slightly, but the striking gap remains.[26] To rationalize limited market activity despite this evidence, there are likely large transaction costs.

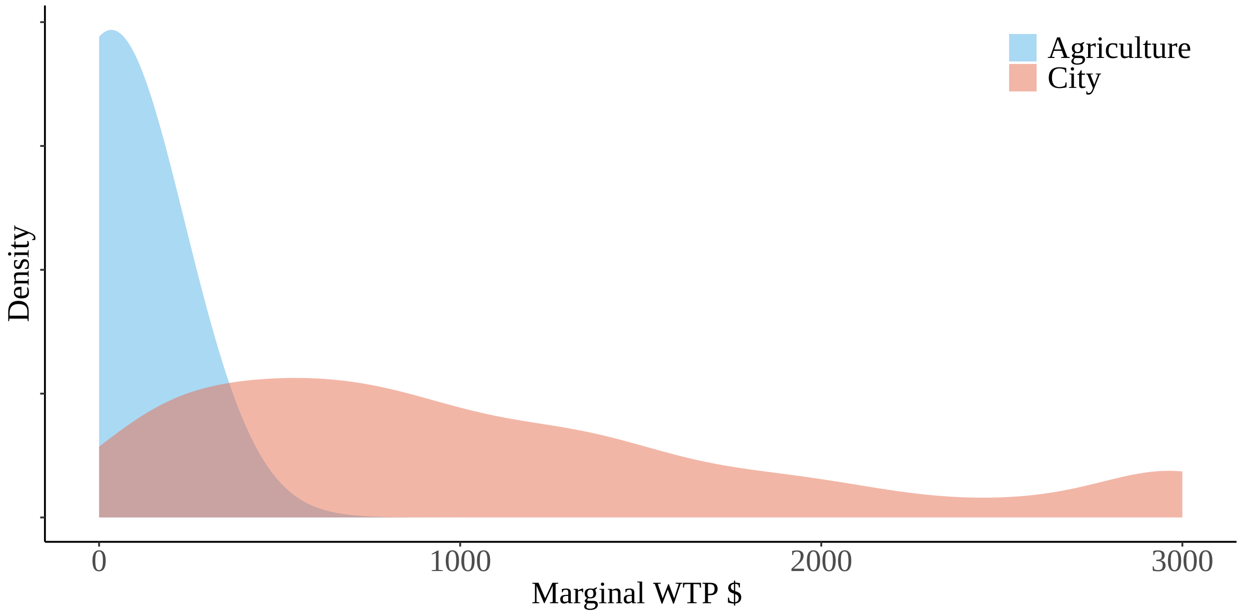
6.3 Estimation of transaction costs

I parameterize transaction costs and estimate by simulated method of moments to match surface water trade moments in California from 2012-2015.

---

[26] In Appendix Figures 17 and 18 I show how the distribution of DAUCO and utility willingness-to-pay shifts higher as drought conditions increase from 2012 to 2015.

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 5.1 and 5.2.

A bilateral trade is subject to transaction cost $\tau_{sbt}(\theta)$ per acre-foot that depends on parameters $\theta = (\tau, \psi, \nu)$, the characteristics of trade, and a structural shock unobserved by the econometrician but observed by the trading agents:

$$\tau_{sbt} = \tau_1\text{AgToAg} + \tau_2\text{CityToAg} + \tau_3\text{CityToCity} + \tau_4\text{AgToCity} + \tag{15}$$

$$\tau_5\text{isRight} + \tau_6\text{ProjectExport} + \tau_7\text{CrossDelta} + \tau_8\text{Distance} + \psi_{r(s)} - \psi_{r(b)} + \nu\varepsilon_{sbt}. \tag{16}$$

Parameters ψ_r are fixed effects for willingness-to-pay of traders from a particular region. Shocks ε_{sbt} are i.i.d. standard normal where ν represents the variance of these shocks. Transaction cost parameters τ_1 through τ_4 represent residual average trade frictions between different kinds of users for water transfers that trade project water, within project, and without crossing the Delta. Parameters τ_5, τ_6, and τ_7 represent the additional friction when traders face the burdens associated with trading a right, approving project water to be traded out of project, and from crossing the Delta. Lastly, the distance parameters τ_8 estimates the transaction cost per mile per acre-foot.

For a given choice of parameters $\hat{\theta}$ and draw of errors ε_{sbt}, I randomly pair up buyers and sellers and enact trade until there are no more willing trading pairs. I summarize the outcomes of this trading protocol with 17 estimated moments $\hat{M}(\hat{\theta}, \varepsilon_{sbt})$ reported in Table 16. To pin down the first 7 parameters, I compute the average annual trade volumes between different uses, of rights, of project exports, and of transfers that cross the Delta. I compute the average distance between buyers and sellers that trade, weighted by the transfer quantity. To estimate the variance parameter ν, I match, using simulated outcomes, the residual variance of the reduced from trade friction regression from

Section 2. Lastly, I compute the net trade of each hydrologic region to calibrate regional parameters ψ.

I implement estimation by simulated method of moments and describe the process briefly here. In Appendix Section B, I describe each step of the trade simulation and estimation in more detail. I draw $R = 100$ error vectors $\{\varepsilon^r_{sbt}\}$ and compute the model's predicted value of each moment and the corresponding average error:

$$\overline{M}(\hat{\theta}) = \frac{1}{R}\sum_{r=1}^{R}\hat{M}\big(\hat{\theta}, \varepsilon^r)\big) \qquad\qquad \overline{e}(\hat{\theta}) = \frac{\overline{M}(\hat{\theta}) - M}{M}$$

I estimate transaction cost parameters $\hat{\theta}$ by minimizing the following average weighted squared-error:

$$\hat{\theta} = \arg\min_{\theta} \overline{e}(\theta)^T W \overline{e}(\theta)$$

Weight matrix W is the inverse variance-covariance matrix of estimated moments which I estimate with a two-step procedure as in Hansen & West (2002).

6.4 Discussion of Trading Model

My model of bilateral transaction costs and trade makes two categories of assumptions that are substantive: trading conduct and interpretation of trade friction parameters.

First, trading conduct is characterized by three key features: bilateral pairs, myopic surplus maximization, and random arrival of trading partners. Each of these modeling choices are chosen to manage heterogeneous transaction costs and interdependence between transfer decisions. In surface water markets, transaction costs depend on the type of water asset, locations, and uses of the trading agents. Incorporating how the cost of distance, the composition of cities/farmers and kinds of water held by each agent aggregate into trade frictions quickly becomes unwieldy. Furthermore, traders in real life must resolve these agent-specific transaction costs, so bilateral transactions are more common. Analyzing bilateral trades both acts as a useful approximation and reflects the bulk of transactions I observe in the data.

However, by restricting to bilateral traders, I have to take a stand on how bilateral pairs determine the quantity to trade. This is particularly relevant since a pair's trading decision will affect the value of those agents' decisions with other trade partners. In my model, I assume that buyers and sellers choose trade quantity to maximize their joint surplus net transaction costs. As a buyer and seller increase their trade quantity, the buyer's marginal value decreases and the seller's increases. At some point, instead of continuing to trade until marginal values (net costs/trading constraints) are equated, it may benefit the agents to stop early and instead trade with other agents. To incorporate this kind of behavior, I would need agents to anticipate trade with other agents. This becomes incredibly complicated very quickly. Furthermore, if I believe that transaction costs are high relative to gains from trade, I do not expect that agents will be making delicate decisions that would require trading with multiple agents. So I view bilateral pairs myopically trading as a useful approximation and one that resembles the high friction environment I study.

Because I make this assumption, the order in which agents myopically trade will change outcomes. This problem is similar to the firm entry models studied in industrial organization where for a given set of parameters, there can be multiple equilibria depending on the order of play. This entry literature often relies on heuristics to complete the model and in this case, enforcing myopic gains and a particular order of trade achieves this. Since I would like results to not hinge critically on the order of trade, I average over random orders.

Ultimately, these parameters capture average gaps in willingness-to-pay along different characteristics of bilateral transaction costs. The second key set of assumptions is my interpretation of transaction cost parameters. While the model includes many detailed features of California's surface water market, it can still suffer from classical omitted-variable bias. For example, transfers of project water that are exported may also face frictions in coordinating/approval from project managers. This specific friction is not required for rights face return flow measurement, but instead rights must coordinate with project infrastructure from the outside. Furthermore, it could be that cross-project transferors are more aware of each other than non-project traders. Unfortunately, in the period where any data is available, there is limited policy variation in California's water market. Instead of benefiting from sharp quasi-random adjustments, I must incorporate everything that I can feasibly include and carefully interpret/caveat my estimates.

7 Results

7.1 Transaction Cost Estimates

The estimation procedure yields the parameter estimates in Table 7. I report the observed and estimated moments in Table 16. For each mile of distance between buyer and seller, each acre-foot transferred is subject to an estimated average distance cost of \$0.53. This cost could both include physical transportation costs and search frictions that increase in distance.

Table 7: Marginal Transaction Cost Estimates

	AgToAg	CityToAg	CityToCity	AgToCity	isRight	ProjectExport	CrossDelta	Distance	Variance of Shock
Cost \$/af	163.01	47.73	2488.5	2704.94	402.43	39.31	21.15	0.53	54.19

Notes: The table reports transaction cost parameter estimates (τ, ψ, ν) that minimize the objective function in Equation 15 on the combined panel data in California from 2012-2015. The distance parameter is in \$/mile×af.

The first four parameter estimates describe average residual frictions when surface water is traded between different uses. For agricultural buyers, trade is subject to transaction costs of \$163/af and \$48/af when the seller is a farmer or buyer, respectively. On the other end, when cities are purchasing water, trade is subject to much higher trade frictions. I estimate an average friction of \$2704/af when farmers try to sell to cities. I think two key issues are the source of high transaction costs for urban buyers. First, utilities often purchase surface water from large regional wholesalers, which creates a supply chain friction between willing buyers and sellers. Second, transfers from cities to farms are often scrutinized both politically and administratively for both the potential economic impact on the local agrarian community and the hydrological impact on the environment or downstream supply (Ferguson & Kashner, 2024).[27]

Any transfer of non-project water held as a right or export of project water requires review that is known to be time-consuming and costly for trading partners. There are two components to this review. First, is verifying the quantity of water held by the seller. Second, is estimating the consumptive use of the seller so that return flow externalities are internalized. Since project water quantities are measured and reported clearly online, project water is not subject to the same scrutiny or measurement required to verify rights. However, the consumptive use computation is the same. I estimate the cost of real water determinations for project sellers at \$39/af. This cost for project real water determinations corresponds to costs associated with measuring consumptive use and evaluating downstream externalities. Transfers of rights, on the other hand, are subject to the higher cost of \$402/af that includes the consumptive use measurement and the verification of the rights. There are potentially reasons other than the cost associated with rights verification that lead to higher transaction costs for rights. Right holders may have less sophisticated infrastructure, less access to storage and inter-temporal management, and increased search costs due to being in out-of-project networks.

Transfers that cross the Delta require additional review to protect fragile Delta ecosystems and avoid harmful saltwater intrusion. I estimate the friction associated with Delta transfers at \$21/af. This cost could reflect not just the administrative process required, but also the uncertainty about the final quantity of water that will be made available. The magnitude of the Delta cost parameter is smaller relative to other frictions that other research has suggested. This is because I directly control for Delta constraints in my trade model and additional costs over-and-above this structural constraint are relatively small.

I make three main conclusions from these transaction costs estimates. First, the costs associated with rights verification, return flow measurement, and crossing the Delta are large relative to agricultural value and frictions. In particular, frictions for farmers trying to sell rights make up the vast majority of the friction. Second, these frictions are small relative to transaction costs associated with city buyers. From these estimates alone, it seems that policy proposals that target streamlining informational frictions and Delta crossings will not alleviate the largest frictions in the market.

Lastly, I emphasize that this structural model that incorporates willingness-to-pay for water along with detailed pairwise transaction costs between farmers and cities results in different conclusions than the reduced form results earlier in this paper and in previous literature (Regnacq et al., 2016, Hagerty, 2023). The results in column (1) of Table 4 suggest that AgToCity frictions are not as large as those for rights, return flow measurement, or Delta crossings. Even column (3), which uses my agricultural and urban models and includes average differences in willingness-to-pay

---

[27] In Appendix Table 10 I provide some reduced form evidence that political opposition in agricultural communities to transferring surface water increases frictions.

between regions, the relative magnitudes of these frictions still seem large in comparison to general AgToCity frictions. An important contribution of this paper is the lesson that incorporating specific gaps in values between buyers and sellers along with their pair-specific transaction costs results in starkly different conclusions than reduced-form evidence suggests.

7.2 Counterfactuals

I analyze the potential economic gains from reducing transaction frictions in California's surface water market. I estimate a series of counterfactuals where I either reduce transaction costs or change how hydrological constraints are managed.[28] I compare the outcomes of each counterfactual regime to the baseline outcomes that match observed moments in the data.

Baseline: In Table 8 I report average annual outcomes using baseline parameters for three drought scenarios: *Dry*, *Normal*, and *Wet*. I report the volume of surface water trade, the increase in surplus for cities and agriculture, the total transaction costs, and the net gain after subtracting trade frictions from total surplus. I also report how many acres are fallowed and how much groundwater is pumped. Trade volumes increase from 161 to 414 thousand acre feet from wet to dry years. Along with this increase in volume, there are increases in gains and surplus. In a wet year, California's entire surface water market only produced \$9.2 million in gains. Water marketing is much more valuable in dry years, producing \$76.9 million in net gains.[29] These dry year gains are small relative to the increase in allocative surplus of nearly \$300 million since 75% of those gains are lost to transaction costs. Despite the potential for trade, fallowed acres still increase greatly from wet to dry years by over 50%, while groundwater pumping remains relatively constant. Table 9 reports these same outcomes relative to baseline levels in various counterfactuals.

Table 8: Baseline Trade Outcomes

Specification		Trade Volume (TAF)	Net Gain (\$M)	Cost (\$M)	City Surplus (\$M)	Ag. Surplus (\$M)	Fallowing (Million Acres)	Pumping (MAF)
Baseline	Dry	414	76.9	221.7	199.7	99	2.3	23.7
	Normal	293	46.1	135.2	115.6	65.6	2	23.6
	Wet	161	9.2	61	31.8	38.4	1.5	23.2

Notes: Table reports the levels of various trading outcomes using baseline estimates, and then reports the relative change in those statistics across various counterfactuals. For each counterfactual outcome, I report the average within types of years: Dry, Normal, and Wet. The table reports estimates on years 2012-2015 where 2012 was Wet, 2013 was Normal, and 2014-2015 were dry.

Return Flow Measurement Costs: First, I consider the trade friction associated with return flow measurement which requires costly estimation of the consumptive use of sellers. Whenever a surface water right is being traded or project water is being exported, the trade is subject to return flow measurement. I assume that the estimated transaction cost of $\tau_6 = \$39.31$/af captures the

---

[28] Appendix Section C.2 lists and explains how each counterfactual is computed.

[29] I note that my estimates of the value of existing market activity are very similar to Hagerty (2023) despite using different data and procedures to estimate willingness-to-pay for surface water.

cost of return flow adjudication for both project water exports and any trade of rights. Under counterfactual *No RF Cost*, I consider subtracting this estimated return flow cost from both project exports and rights trade. This counterfactual captures the value of information about consumptive use to market activity. By removing the cost, the surface water market sees an increase in trade volume of about 25% across all drought scenarios, with an additional 58 taf of trade in dry years. This increased trade corresponds to $16.1 million dollars of allocative surplus in dry years and almost entirely benefits farmers, with little surplus to cities. These gains correspond to only a 0.4% increase in agricultural profits.

To achieve these gains, the cost of return flow measurement would need to be eliminated. The development of more precise satellite technology and sophisticated predictive algorithms, directly observing the consumptive use of farmers in real time is becoming possible. California could determine adjustments to return flows through a streamlined process that incorporates these kinds of models without imposing burdensome administrative processes.

However, if these new measurement technologies prove inaccurate, overly manipulable, or too impractical to implement, I propose another policy measure. Instead of determining the consumptive of the farmer by evaluating the crop choices and environmental conditions of different agricultural regions over the last five years of production, what if a constant consumptive share was applied to all transfers, independent of production choices? In Figure 7, I report dry-year allocative gains under different choices for this constant return flow adjustment share ranging from 0.5 to 1. For example, under a counterfactual with return flow adjustment share 0.5, buyers can only divert 50% of the seller's reduced diversion. The un-diverted water remains in the system to address return flow externalities, but if the choice of adjustment is more conservative than true consumptive shares, the water increases the environmental supply of water for in-stream flows, wild and scenic rivers, managed wetlands, and Delta outflow.

On the x-axis, I report the additional environmental water supply made available by the associated return flow regulations. On the y-axis I report the average dry years gains in allocative surplus relative to the baseline scenario. In the event that return flow externalities harm other users, which will not happen in scenarios where sellers' true consumptive shares are known, I subtract surplus losses to impacted parties. The box point in the plot represents the baseline specification where return flow information is costly and the asterisk shows the increase in surplus under perfect information where return flow measurement costs are eliminated. Along the frontier, I plot outcomes under different choices of constant return flow shares that increase in the opacity of the line from 0.5 to 1.

Under lower shares, much more water is left to the environment, but the wedge between buyer and seller values increases, decreasing gains from trade. On the other hand, as shares increase environmental flows decrease and can even bend surplus downward as downstream agents experience negative externalities from trade. The aggregate outcomes plotted on the axes mask heterogeneity in negative externalities where some farmers, cities, or environments may experience gains whereas other are hurt. The triangle point depicts the largest share, in this case 0.72, that can be chosen

Table 9: Counterfactual Results Relative to Baseline

Counterfactual		Trade Volume (TAF)	Net Gain ($M)	Cost ($M)	City Surplus ($M)	Ag. Surplus ($M)	Fallowing %	Pumping %
No RF Cost	Dry	58	2.1	13.9	0.6	15.5	-0.02	0.09
	Normal	46	1.2	12.3	0.2	13.3	-0.06	0.07
	Wet	36	0.7	8.6	0.1	9.1	-0.01	0.05
No Delta Friction	Dry	336	14.7	91.7	1.8	104.6	0.14	0.27
	Normal	218	8.4	56.8	1.9	63.4	-0.09	0.21
	Wet	122	3.5	32.1	1.9	33.7	0.06	0.08
No Delta Friction, No RF Cost	Dry	415	17.1	110.5	2.4	125.3	0.13	0.37
	Normal	295	10.2	76.8	2.3	84.7	-0.11	0.27
	Wet	185	4.8	46.9	2	49.7	0.06	0.16
No Delta Friction, No Right/RF Cost	Dry	1241	46.3	312	5.3	353	0.41	1.32
	Normal	934	30.6	231.3	6.3	255.6	0.22	0.94
	Wet	638	19.6	153.5	2.4	170.7	0.84	0.41
No AgToCity Friction	Dry	387	230.3	34.8	278.9	-13.8	0.81	1.29
	Normal	355	178.3	53.1	239.5	-8.2	0.59	1.17
	Wet	366	142.3	84	229.3	-3	0.63	1.26
No AgToCity, No Delta Friction, No RF Cost	Dry	745	258	117.6	271.4	104.2	2.08	2.83
	Normal	599	200.4	107.6	238.5	69.5	1.24	2.29
	Wet	515	160.8	111	228.3	43.5	0.9	1.82
No AgToCity, No Delta Friction, No Right/RF Cost	Dry	1601	342.8	252.2	267.1	327.9	1.13	2.65
	Normal	1292	267.1	209.9	237.6	239.4	0.88	2.18
	Wet	1018	221.2	172.3	231.7	161.8	1.47	1.79

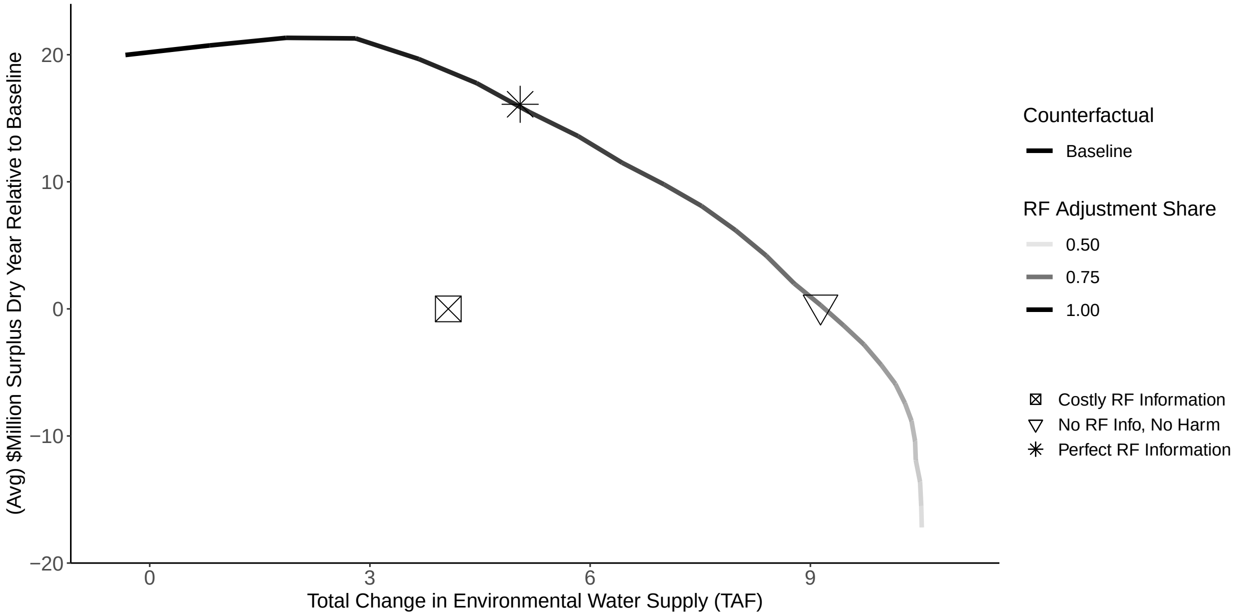
Notes: Table reports the levels of various trading outcomes using baseline estimates, and then reports the relative change in those statistics across various counterfactuals. For each counterfactual outcome, I report the average within types of years: Dry, Normal, and Wet. The table reports estimates on years 2012-2015 where 2012 was Wet, 2013 was Normal, and 2014-2015 were dry.

while insuring that no agent or region experiences a negative externality. The best constant consumptive share policy that would not require return flow measurement costs and insures no injury to downstream uses produces about the same gains as the baseline regime where traders endure the administrative costs required to determine true consumptive shares.

I interpret these conclusions as a negative result for potential return flow management policy solutions to California's surface water market. First, even under an ideal world of perfect information, gains are small. Second, feasible policies to reduce return flow costs are no better than the costly information baseline. Return flow management policies, on their own, are unlikely to improve outcomes. However, some results suggest that these solutions are worth considering in combination with other policies.

Delta Bottleneck: Next, I consider frictions associated with the Delta. There are structural constraints that mandate surface water crossing the Delta must leave carriage water of 22% for

Figure 7: Surplus Gains Across RF Constraint Counterfactuals



Notes: Figure depicts average allocative gains from trade in dry year scenarios against the change in environmental water supply induced by trade. The color indicates which frictions are present for the box point, where costs to measure return flows of sellers are present. The asterisk represents an alternative where return flow measurement costs are removed. The frontier removes measurement costs and instead applies a constant consumptive share to all sellers. The triangle indicates the choice of constant consumptive share where no agents or or environmental regions are negatively impacted by trade.

Sacramento River water and conveyance water of 10% for San Joaquin River water (PPIC 2021). Additionally, to adjudicate these restrictions, transfers crossing the Delta must undergo an administrative review and careful management. I estimate that the friction from crossing the Delta, after adjusting for the Delta carriage water constraints, is $21/af.

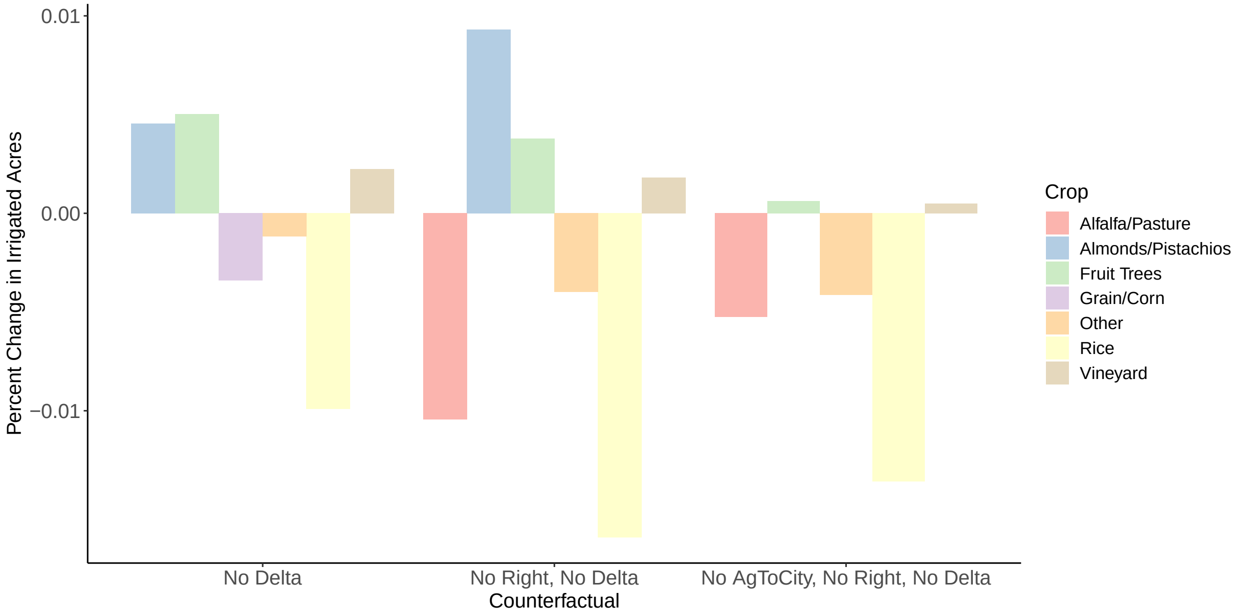
In counterfactual *No Delta Friction*, I remove both carriage water requirements and estimated transaction costs for Delta crossings.[30] In dry years, trade volumes nearly double with an additional 336 taf. This yields agricultural surplus of $104.6 million, equivalent to 3% of agricultural profits, and benefits cities at nearly $2 million. In Figure 8 I show the percent change in irrigated acres for the most impacted crops and find production shift from low to high value crops. Removing Delta frictions increases almonds/pistachios, fruit trees, and vineyard production around 0.5% and decreases grain/corn and rice, with rice seeing the largest losses of 1%.

Under specification *No Delta Friction, No RF Cost*, I additionally remove return flow measurement costs. This increases surplus by around 80 taf in both dry and normal years and increases allocative surplus by around 20%. However, in Figure 9 I find a similar conclusion to the previous counterfactual where responsible choices of constant return flow adjustments that do not disrupt any third-parties cannot produce more value than paying return flow costs to get exact consumptive

---

[30] In Appendix Table 19, I decompose gains between removing hydrological constraints and transaction costs. I find that the constraints and unexplained additional costs provide equivalent frictions to California's surface water market.

Figure 8: Largest Crop Switching by Selected Counterfactuals



Notes: Figure shows the percent change in irrigated acres for the three most positively and negatively affected crops. I show this percent change for three counterfactuals corresponding to removing Delta frictions, additionally removing right verification costs, then additionally removing AgToCity frictions. Percent changes are averaged over all years 2012-2015. In Appendix Figure 23 I show the same plot in acres instead of percent changes.

use information.

These results suggest that structural constraints surrounding Delta management are very important to understanding surface water market frictions and choices in return flow management again do not matter very much. A counterfactual regime without Delta constraints is not just a hypothetical proposal, but a potential solution since California is currently considering building the Delta Conveyance Project that would bypass carriage water requirements and limits on exports in the Delta. While this analysis shows that this proposed infrastructure would improve surface water marketing, the gains without addressing other water market transaction costs are small relative to the pipelines' expected construction cost of $20 billion.[31]

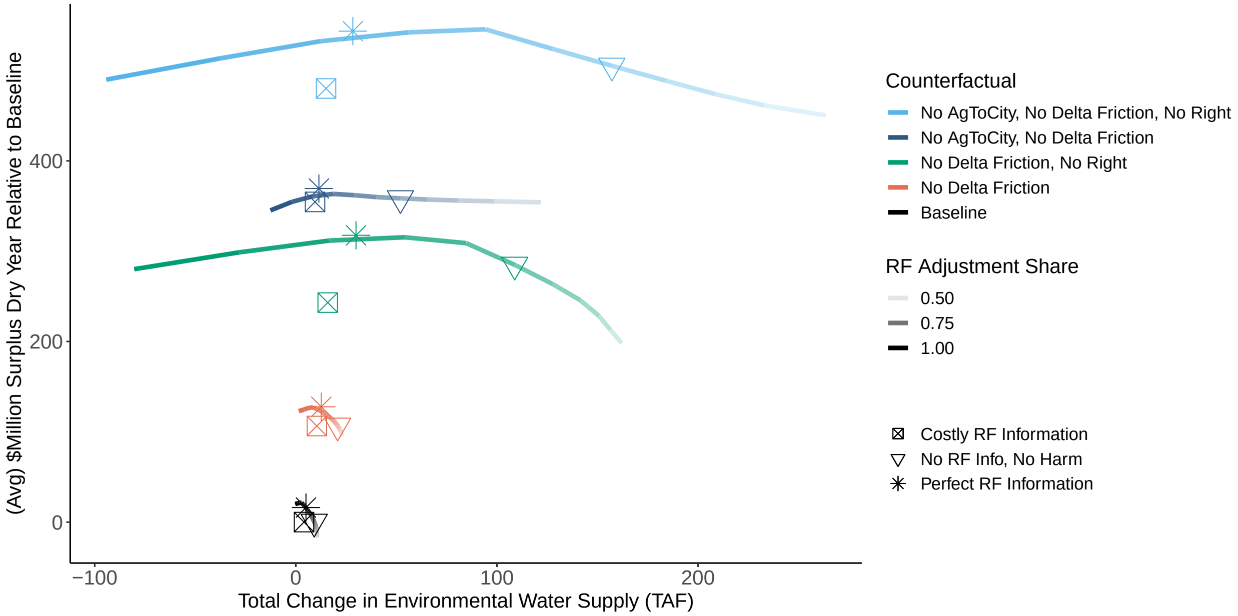
Rights Verification: I also consider how frictions associated with trading rights affect market performance. Rights are often ambiguous, not digitized, and quantities are not updated annually, so buyers cannot easily find the quantity of water that sellers have and any proposed trade requires verifying the right and determining the quantity of water the seller is entitled to that year. I consider outcomes if California were able to successfully eliminate the remaining friction associated with trading rights in addition to building the Delta conveyance project under counterfactual *No Right/RF/Delta Cost*.

I show that trade volumes increase significantly with dry years trade volumes reaching 1.24 million acre-feet. Agricultural allocative gains reach $353 million - over 10% of agricultural profits.

---

[31] There are other reasons to consider building the Delta conveyance project that justify the costs including earthquake resilience, minimizing pumping restriction volatility, and minimizing impact of Delta ecosystems (PPIC 2022).

Figure 9: Surplus Gains Across RF Constraint Counterfactuals



Notes: Figure depicts average allocative gains from trade in dry year scenarios against the change in environmental water supply induced by trade. The color indicates which frictions are present for the box point, where costs to measure return flows of sellers are present. The asterisk represents an alternative where return flow measurement costs are removed. The frontier removes measurement costs and instead applies a constant consumptive share to all sellers. The triangle indicates the choice of constant consumptive share where no agents or or environmental regions are negatively impacted by trade.

City gains remain low given the large transaction costs required to purchase water from farmers. Farmers shift away from low value alfalfa and rice crops and produce 1% more almonds/pistachios, as shown in Figure 8. In Figure 10 I map how groundwater pumping and fallowing changes across DAUCOs.[32] Since surface water is reallocated from low cost groundwater areas north of the Delta to over-drafted basins south of the Delta, pumping responds accordingly. These results demonstrate how surface water markets can act as a tool for reducing pumping in critically over-drafted basins and adapting to SGMA regulation.[33] Because of groundwater substitution, the fallowing response is not as prominent.

In Figure 9, the simple policy proposal to apply constant return flow adjustments to all trades has more bite. The counterfactual indicated with the triangle applies consumptive share 0.7 to all sellers and achieves over 2/3 of the gains between costly and no-cost exact consumptive share measurement. Furthermore, this proposal yields the additional benefit of 100 taf acre-feet for environmental uses.

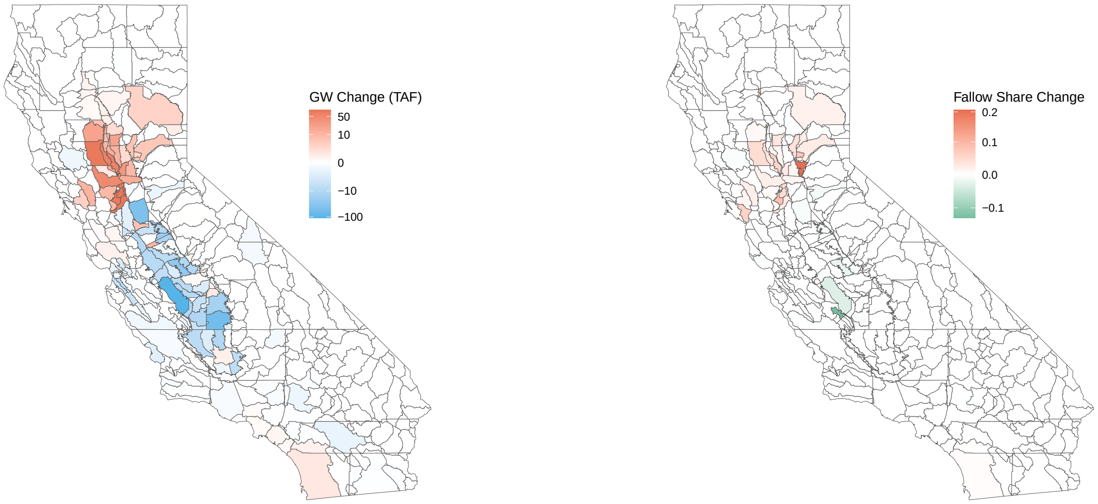
The potential policies to achieve these gains first require the construction of the Delta pipeline and the adoption of constant return flow adjustments at a level of 0.7. Policies to eliminate the

---

[32] In Appendix Figures 21 and 22 I produce these plots for other main counterfactuals.

[33] However, this paper does not incorporate the potential for groundwater pumping externalities. This creates two missing contributions to welfare. First, the benefits of reducing overdraft are not incorporated. Second, the harms and potential externalities from increased pumping north of the Delta are not understood. As hydrological models on the nexus between surface and groundwater resources improves, they can be included to enrich estimates of welfare and add necessary constraints to trade.

Figure 10: No Right/RF, No Delta Friction Agricultural Response by DAUCO



(a) Change in Groundwater Pumping

(b) Percentage Point Change in Fallowing Share

Notes: Panels (a) and (b) depict the logged average return flow contributions and dependence of each DAUCO from 2005-2015.

cost associated with rights are more complicated. First, policymakers think that digitization of rights and ex-ante, accessible reporting of how much water each right holder is entitled to will reduce this friction. However, I anticipate that much of the friction associated with rights may be related to less advanced connectivity to canal infrastructure, less access to storage and inter-temporal management, and increased search costs due being in out-of-project networks. In future work, I hope to develop research designs that may provide a clearer decomposition of the frictions and policies that can best liberalize trade of surface water rights.

AgToCity Frictions: I next consider the counterfactual that eliminates the residual friction associated with agricultural to urban transfers. Under counterfactual *No AgToCity Friction* I eliminate the AgToCity cost from transactions costs and keep all other baseline specifications. I find that this adjustment alone produces more net gains than any other specification considered this far, despite the lower trade volumes. Trade volumes increase between 366 and 387 taf across drought scenarios and net gains stretch from $142 to $230 million. In this counterfactual, since hydrological frictions remain unchanged, all the allocative surplus gains are attributed to cities and agricultural surplus decreases from all the water traded away from farmers. This decrease in agricultural surplus is associated with a 0.5-0.8% increase in fallowing.

Combining the removal of AgToCity frictions with the previous policy proposal, I report even more impressive gains under specification *No AgToCity, No Delta Friction, No Right/RF Cost.* This counterfactual, as opposed to all other specifications, greatly benefits both farmers and cities with total surplus gains of nearly $600 million in dry years. Figure 8 shows that increased trade to cities makes it so that only fruit trees and vineyards benefit from other reduced transaction costs, and instead there are larger reductions in low value crops. Figure 9 depicts how eliminating return flow measurement costs is only valuable if right costs are eliminated, but when they are along with reduced AgToCity frictions, the simple constant return flow share proposal is worth it.

The model in this paper cannot speak to specific policies that will address frictions between agricultural sellers and urban buyers. The average friction of \$2705/af associated with agricultural to urban transfers captures many different forces. Primarily, given qualitative research into AgToCity transfers, I hypothesize that much of this transaction cost is due to political economy frictions where farmers are worried that agricultural exports of surface water will harm their local agrarian communities. However, the cost may also include average search frictions due to limited to social connections between agricultural and urban communities, increased environmental impacts from changing uses, and general repugnance to city uses of water that may be viewed as less socially valuable than agricultural production. Ongoing work is attempting to identify which of these explanations is legitimate and which can be addressed with feasible policy solutions.

In Appendix Table 19, I report a series of other counterfactuals that I view more as benchmarks rather than results to guide policy development.[34] In counterfactual *No Distance Cost*, by removing the transaction cost associated with distance, which may capture both physical conveyance costs and search costs that increase with distance, trade volumes reach as large as 1.89 maf in normal drought condition years and average agricultural surplus are above \$300 million in all drought scenarios. City experience very limited gains from the elimination of distance costs. If all frictions are eliminated, average surplus gains are over \$1.3 billion across all drought scenarios, indicating that surface water misallocation is large and that friction-less trade or pricing water for all users in the state may yield incredible gains.

7.3 Implications for Water Market Design

I takeaway three main lessons from these counterfactuals. First, frictions associated with return flow measurement are relatively small and simple policies that can eliminate these costs produce modest gains. Reducing rights frictions can make return flow policy proposals valuable, but this would require high levels of market liberalization with policy tools that need further research. Second, the proposed Delta pipeline infrastructure produces non-trivial gains equivalent to 3% of agricultural profits that do not justify the project alone, but in conjunction with existing motivation for the project, support the completion of the project. Lastly, many frictions remain. There are still \$160/af of agricultural frictions that cannot be explained by distance or the other policies of interest. Potential pecuniary externalities to trade create political economy frictions for agricultural sellers, so other work estimates these local economic externalities to selling water (Ferguson and Kashner 2024). Moreover, frictions for urban buyers remain large and understanding wholesaler-utility supply chains and contracts may provide the highest value solutions to surface water market misallocation.

---

[34] Appendix Tables 17 and 18 show the percent change in irrigated acres for each crop across all counterfactuals.

8 Conclusion

This paper analyzes trade frictions in California's surface water market and highlights the kinds of policies that may increase market activity and re-allocate scarce water resources. To estimate frictions and simulate counterfactual policies, I construct a panel of water use, supply, and trade from 2005-2015. With this novel combination of data sources, I build and estimate a structural model of agricultural production, urban demand, hydrological externalities, and bilateral transaction costs.

Surface water markets are known to exhibit high transaction costs but the literature has not provided clear insight into the quantitative decomposition of frictions, which has made targeted policy solutions more difficult to motivate. In particular, policy discussions have centered around the administrative burden of approving surface water transactions so that rights can be clarified, externalities internalized, and environmental constraints satisfied. I am able to directly estimate gains from interventions in these spheres and draw five main conclusions.

First, the administrative costs associated with measuring consumptive use and managing return flows are relatively low and no-information management rules are not worth the potential gains. Information about consumptive use is valuable, but policies that focus on reducing the return flow measurement costs are unlikely to improve welfare.

Second, infrastructural investment in the Delta conveyance project relaxes costly constraints and can increase agricultural profits by 3%. The gains from such an investment should be considered in the ongoing cost-benefit analysis of the Delta conveyance project which is expected to cost $20 billion. Freeing up trade across the Delta is valuable for other market interventions as well.

Third, trading surface water rights is costly and any efforts to digitize records and ex ante verification of rights' quantities each year could significantly increase market activity. Combining streamlined rights verification with Delta infrastructure and a simple rule to circumvent consumptive use measurement could increase agricultural profits by 10% and provide over 100 thousand acre-feet of additional surface water to environmental uses.

Fourth, residual frictions, especially for urban buyers, remain large. Understanding why these frictions are so large and designing mechanisms to overcome them is an area of ongoing and future research (Ferguson & Kashner, 2024, Ferguson & Liu, 2024).

Lastly, the incorporation and buyer-seller specific transaction costs along with a structural model of hydrological constraints and willingness-to-pay results in a different set of agenda items for water policy design than reduced form evidence was able to motivate. Administrative costs associated with third-party and environmental externalities are non-trivial, but will not close the largest gaps in value for water in California. Understanding the supply chain and political economy frictions in surface water markets could provide the most impactful solutions to market failure in California.

References

Anderson, D. B. (2012). Water transfer approval: Assuring responsible transfers. Prepared by Staff Counsel IV, California Department of Water Resources.

Arbués, F., García-Valiñas, M. , & Martínez-Espiñeira, R. (2003). Estimation of residential water demand: A state-of-the-art review. *The Journal of Socio-Economics*, *32*(1), 81–102.

Aronoff, D., & Rafey, W. (2023). Conservation priorities and environmental offsets: Markets for florida wetlands. Unpublished Manuscript.

Boretti, A., & Rosa, L. (2019). Reassessing the projections of the world water development report. *NPJ Clean Water*, *2*, Article No. 15.
URL https://doi.org/10.1038/s41545-019-0039-9

Burlig, F., Preonas, L., & Woerman, M. (2024). Groundwater and crop choice in the short and long run. Unpublished Manuscript.

Carpentier, A., & Letort, E. (2014). Multicrop production models with multinomial logit acreage shares. *Environmental and Resource Economics*, *59*, 537–559.

Carpentier, A., Letort, E., & Stenger, A. (2015). Economic modelling of agricultural production: Past advances and new challenges. *Revue d'Etudes en Agriculture et Environnement–Review of Agricultural and Environmental Studies*.

Chong, H., & Sunding, D. (2006). Water markets and trading. *Annual Review of Environment and Resources*, *31*(1), 239–264.

Colby, B. (1990). Transactions costs and efficiency in western water allocation. *American Journal of Agricultural Economics*, *72*(5), 1184–1192.
URL https://www.jstor.org/stable/1242530

Donna, J., & Espin-Sanchez, J. (2018). The illiquidity of water markets: Efficient institutions for water allocation in southeastern spain. Unpublished Manuscript.

Ferguson, B., & Kashner, Z. (2024). Is water a keystone resource? local externalities to surface water trade in the murray-darling basin. Working Paper.

Ferguson, B., & Liu, B. (2024). Robust rights to the commons. Working Paper.

Ferguson, B. A., & Milgrom, P. (2024). Market design for surface water. Working Paper w32010, National Bureau of Economic Research.

Gupta, M., Hughes, N., & Wakerman Powell, K. (2018). A model of water trade and irrigation activity in the southern murray-darling basin. Unpublished Manuscript.

Hagerty, N. (2023). What holds back water markets? transaction costs and the gains from trade. Working paper.

Hanemann, M., & Young, M. (2020). Water rights reform and water marketing: Australia vs the us west. *Oxford Review of Economic Policy*, *36*(1), 108–131.
URL https://doi.org/10.1093/oxrep/grz037

Hansen, B. E., & West, K. D. (2002). Generalized method of moments and macroeconomics. *Journal of Business & Economic Statistics*, *20*(4), 460–469.
URL https://doi.org/10.1198/073500102288618603

Ito, K. (2014). Do consumers respond to marginal or average price? evidence from nonlinear electricity pricing. *American Economic Review*, *104*(2), 537–563.

Leonard, B., Costello, C., & Libecap, G. (2019a). Expanding water markets in the western united states: Barriers and lessons from other natural resource markets. *Review of Environmental Economics and Policy*, *13*(1), 43–61.

Leonard, B., Costello, C., & Libecap, G. D. (2019b). Expanding water markets in the western united states: barriers and lessons from other natural resource markets. *Review of Environmental Economics and Policy*, *13*(1), 43–61.

Rafey, W. (2023). Droughts, deluges, and (river) diversions: Valuing market-based water reallocation. *American Economic Review*, *113*(2), 430–471.

Regnacq, C., Dinar, A., & Hanak, E. (2016). The gravity of water: Water trade frictions in california. *American Journal of Agricultural Economics*, *98*(5), 1273–1564.

Russo, A., & Aspelund, K. M. (2024). Additionality and asymmetric information in environmental markets: Evidence from conservation auctions. Working Paper.

Ryan, N., & Sudarshan, A. (2022). Rationing the commons. *Journal of Political Economy*, *130*(1), 210–257.

Scott, P. (2014). Dynamic discrete choice estimation of agricultural land use. Unpublished Manuscript.

Teytelboym, A. (2019). Natural capital market design. *Oxford Review of Economic Policy*, *35*(1), 138–161.
URL https://doi.org/10.1093/oxrep/gry030

Thompson, B. H., Leshy, J. D., & Abrams, R. H. (2013). Legal control of water resources.

Timmins, C. (2002). Measuring the dynamic efficiency costs of regulators' preferences: Municipal water utilities in the arid west. *Econometrica*, *70*(2), 603–629.

Vaux, H. J., & Howitt, R. E. (2018). Managing water scarcity: An evaluation of interregional transfers. In *Economics of Water Resources*, (pp. 95–102). Routledge.

Worthington, A. C., & Hoffman, M. (2008). An empirical survey of residential water demand modelling. *Journal of Economic Surveys*, *22*(5), 842–871.

Young, R. A. (1986). Why are there so few transactions among water users? *American Journal of Agricultural Economics*, *68*(5), 1143–1151.
URL https://doi.org/10.2307/1241865

Appendix

Table of Contents for Appendix

Contents

A Agricultural Production

A.1 Smooth Approximation

Farmer i has L_i acres of land. For each season t, he chooses shares s_{ikt} of land to allocate to each crop $k \in K$. Farmers make non-water profit of π_{ikt} per acre. To produce crops, there is farmer-crop-specific applied water per acre aw_{ikt} that depends on soil, land topography, irrigation efficiency, etc. Farmers treat the maximization of productivity of a given crop-acre as independent from the multi-acreage crop choice problem. For choices of s_{ikt}, I have that $GW_{it} = \sum_k aw_{ikt} s_{ikt} L_i - SW_{it}$.

I capture crop-rotation benefits, quasi-fixed inputs of labor and capital, and constraints on timing of harvest/irrigation with an acreage management cost function $D(\{s_{ikt}\}_k) = d_{it}^{-1} \sum_k s_{ikt} \ln s_{ikt}$ which will motivate crop diversification (Carpentier and Letort 2014). The farmer wants to maximize profits:

$$\Pi_{it}^* = \arg\max_{s_{ikt}} \sum_k L_i s_{ikt} \pi_{ikt} - C_{it}(\sum_k aw_{ikt} s_{ikt} L_i - SW_{it}) - d_{it}^{-1} \sum_k s_{ikt} \ln s_{ikt} \tag{17}$$

$$s.t. \sum_k s_{ikt} = 1, s_{ikt} \geq 0. \tag{18}$$

To optimize farmer profit, I take first order conditions of the Lagrangian:

$$\mathcal{L} = \sum_k L_i s_{ikt} \pi_{ikt} - C_{it}(\sum_k aw_{ikt} s_{ikt} L_i - SW_{it}) - d_{it}^{-1} \sum_k s_{ikt} \ln s_{ikt} - \lambda_{it}^S (\sum_k s_{ikt} - 1). \tag{19}$$

$$\frac{\partial \mathcal{L}}{\partial s_{ikt}} = L_i \pi_{ikt} - \frac{\partial C_{it}}{\partial s_{ikt}} - d_{it}^{-1}(\ln(s_{ikt}) + 1) - \lambda_{it}^S \tag{20}$$

$$= L_i \pi_{ikt} - L_i \underbrace{aw_{ikt} P_{it}^e \rho_i \big(H_{it} + \gamma_i GW_{it}\big)}_{\Gamma_{ikt}} - d_{it}^{-1}(\ln(s_{ikt}) + 1) - \lambda_{it}^S \tag{21}$$

$$= L_i(\pi_{ikt} - \Gamma_{ikt}) - d_{it}^{-1}(\ln(s_{ikt}) + 1) - \lambda_{it}^S. \tag{22}$$

Choosing shares to satisfy the FOC in Equation (21) I get:

$$s_{ikt} = \exp\Big\{ d_{it} L_i (\pi_{ikt} - \Gamma_{ikt}) \Big\} \exp\Big\{ - (d_{it} \lambda_{it}^S + 1) \Big\} \tag{23}$$

Using that shares sum to 1 and by letting $d_{it} = \frac{d}{L_i}$:

$$s_{ikt} = \exp\left\{ \underbrace{d_{it} L_i (\pi_{ikt} - \Gamma_{ikt})}_{\Psi_{ikt}} \right\} \left[\sum_k \exp\{\Psi_{ikt}\} \right]^{-1} \tag{24}$$

$$= \exp\left\{ \underbrace{d(\pi_{ikt} - \Gamma_{ikt})}_{\Psi_{ikt}} \right\} \left[\sum_k \exp\{\Psi_{ikt}\} \right]^{-1} \tag{25}$$

Letting $0 \in K$ represent fallowing which has $aw_{i0t} = 0$ and assuming $\pi_{i0t} = 0$, the (locally) optimal share of crop k satisfies the condition that the scaled log share relative to fallowing is equal to the acre-level non-water profit less the marginal cost of groundwater.

$$\ln\left(\frac{s_{ikt}}{s_{i0t}}\right)/d = \pi_{ikt} - \Gamma_{ikt}. \tag{26}$$

A.2 Acre-level Micro-foundation

As described in Section 5.1, the farmer's problem is to choose a crop function $k^*(a)$ that maps each acre to a crop to maximize total profits:

$$\begin{aligned} k^*(\cdot) &= \underset{k(\cdot)}{\arg\max} \sum_{a \in L_i} \pi_{ik(a)t} + \nu\varepsilon_{ak(a)t} - C_{it}(GW_{it}) && (27) \\ &= \underset{k(a)}{\arg\max} \sum_{a \in L_i} \pi_{ik(a)t} + \nu\varepsilon_{ak(a)t} - C_{it}\Big(\sum_{a \in L_i} aw_{ik(a)t}\Big) && (28) \end{aligned}$$

This problem has a smooth approximation whose solution, for a choice of parameter ν, matches the solution in Equation 26. A component $k^*(a)$ of the optimal crop portfolio can be chosen while fixing all other acres $b \neq a$ by:

$$k^*(a) = \underset{k \in K}{\arg\max}\, \pi_{ikt} + \nu\varepsilon_{akt} - C_{it}\Big(aw_{ikt} + \sum_{b \neq a} aw_{ik^*(b)t}\Big) \tag{29}$$

$$= \left\{k:\ \text{s.t. } \forall j,\ \pi_{ikt} + \nu\varepsilon_{akt} - C_{it}\big(aw_{ikt} + \sum_{b \neq a} aw_{ik^*(b)t}\big) \geq \pi_{ijt} + \nu\varepsilon_{ajt} - C_{it}\big(aw_{ijt} + \sum_{b \neq a} aw_{ik^*(b)t}\big)\right\} \tag{30}$$

$$\approx \left\{k:\ \text{s.t. } \forall j,\ \pi_{ikt} + \nu\varepsilon_{akt} - aw_{ikt}P^e_{it}\rho\big(H_{it} + \gamma_i(GW^*_{it})\big) \geq \pi_{ijt} + \nu\varepsilon_{ajt} - aw_{ijt}P^e_{it}\rho\big(H_{it} + \gamma_i(GW^*_{it})\big)\right\} \tag{31}$$

$$= \left\{k:\ \text{s.t. } \forall j,\ \pi_{ikt} + \nu\varepsilon_{akt} - \Gamma_{ikt} \geq \pi_{ijt} + \nu\varepsilon_{ajt} - \Gamma_{ijt}\right\} \tag{32}$$

The approximation in line (30) is accurate since aw is small relative to total groundwater GW. For any given acre, I compute the ex-ante probability that crop k is chosen:

$$\begin{aligned} s_{akt} &\approx \text{Prob}\left\{\pi_{ikt} + \nu\varepsilon_{akt} - \Gamma_{ikt} \geq \pi_{ijt} + \nu\varepsilon_{ajt} - \Gamma_{ijt},\ \forall j\right\} && (33) \\ &= \text{Prob}\left\{\nu^{-1}(\pi_{ikt} + -\Gamma_{ikt}) + \varepsilon_{akt} \geq \nu^{-1}(\pi_{ijt} + -\Gamma_{ijt}) + \varepsilon_{ajt},\ \forall j\right\} && (34) \\ &= \exp\left\{\nu^{-1}(\pi_{ikt} - \Gamma_{ikt})\right\}\left[\sum_j \exp\left\{\nu^{-1}(\pi_{ijt} - \Gamma_{ijt})\right\}\right]^{-1}. && (35) \end{aligned}$$

Letting $d = \nu^{-1}$ I unite the models with the (local) optimality condition in (34) matching condition (24). The relationship between these models provides an additional micro-foundation for the management cost function of Carpentier & Letort (2014). Since the relationship between these models requires that ν is scaled by the total amount of land, I provide additional guidance on how to estimate the coefficient on the management cost function. Future research on understanding how the level at which T1EV shocks are modelled, the total amount of land, and entropy all relate will provide further intuition and understanding about these crop choice models.

B Details on Trade Friction Estimation

B.1 Trade Model Primitives

Agents include agricultural DAUCOs and urban utilities and can either be sellers or buyers. For each agent i and year t, the estimation will use the following.

W_{ikt} : agent i's water in year t of water asset type $k \in \{\text{Right}, \text{SWP}, \text{CVP}\}$.

$W_{it} = \sum_k W_{ikt}$: total surface water.[35]

κ_{it} : consumptive share of agent.

$V_{it}(\cdot)$: estimated willingness-to-pay function for surface water.

Since the sale of different types of water assets interacts with buyer identity to determine regulations and transaction costs, a bilateral trading pair is a $(s, b) = (\text{Seller} \times \text{Water Asset Type}, \text{Buyer})$. Recall constant marginal transaction cost function τ_{sbt} for bilateral trade:

$$\begin{gathered}\tau_{sbt} = \tau_1 \text{AgToAg} + \tau_2 \text{CityToAg} + \tau_3 \text{CityToCity} + \tau_4 \text{AgToCity} + \\ \tau_5 \text{isRight} + \tau_6 \text{ProjectExport} + \tau_7 \text{CrossDelta} + \tau_8 \text{Distance} + \psi_{r(s)} - \psi_{r(b)} + \nu \varepsilon_{sbt}.\end{gathered}$$

Each component of the transaction cost is determined as follows:

1. AgToAg : s and b are DAUCOs.
2. CityToAg : s is a utility and b is a DAUCO.
3. CityToCity : s and b are utilities.
4. AgToCity : s is a DAUCO and b is a utility.
5. isRight : water asset of seller s is a $k = \text{Right}$.
6. ProjectExport : when the water asset of seller s is project water $k \in \{\text{SWP}, \text{CVP}\}$ and the buyer b is not in the project, $\sum_t W_{bkt} = 0$.
7. CrossDelta : Seller s is upstream the Delta and the buyer b is downstream canal infrastructure that pumps out of the Delta.
8. Distance : The shortest distance (in miles) between buyer and seller restricted to the stream and canal network.

---

[35] For utilities, this includes groundwater which I leave fixed and cannot be traded.

The transaction costs described above are not the only frictions to bilateral trade. There is also the structural adjustment $\alpha(s,b)$ to traded water to satisfy regulatory constraints and hydrological feasibility. In the baseline estimation, this function that restricts the diversion of buyers relative to the seller's reduction is

$$\alpha(s,b) = \underbrace{(1 - \text{CrossDelta}_{sb} \cdot CW_{sb})}_{\text{Delta constraint}} \times \underbrace{(\text{isRight}_{sb} + \text{ProjectExport}_{sb}) \cdot \kappa_{st}}_{\text{Internalize Return Flow}} \tag{36}$$

where carriage water share CW_{sb} is 0.22 if the seller is in the Sacramento River region and 0.10 if the seller is in the San Joaquin River region. Combining these details, the optimal trade between any buyer and seller given water assets, values, structural adjustments, and transaction cost parameters $\theta = (\tau, \psi, \nu)$ is:

$$w^* = \arg\max_{w} \overbrace{\Big(V_{st}(W_{st} - w) - V_{st}(W_{st})\Big)}^{\text{Seller Loss}} + \overbrace{\Big(V_{bt}(W_{bt} + \alpha(s,b)w) - V_{bt}(W_{bt})\Big)}^{\text{Buyer Gain}} - \overbrace{\tau_{sbt}(\theta)w}^{\text{Transaction Cost}}$$

$$\text{s.t } 0 \leq w \leq W_{skt}.$$

B.2 Trade Model Algorithm and Moment Computation

For a given choice of parameters θ, draw of structural errors ε_{sbt} to bilateral transaction costs, and random permutation order of bilateral pairs σ_{sbt}[36], I compute the 17 moments $\hat{M}(\theta, \varepsilon^r)$ as described in the algorithm box below.[37]

```
Algorithm 1: Computing Moments from Bilateral Surface Water Transfers
    Data: Agent primitives, trade shocks $\varepsilon$, cost parameters $\theta$, permutation of bilateral pairs $\sigma$
    $\hat{M}(\theta, \varepsilon, \sigma) \leftarrow 0$;
    for (s,b) in order of $\sigma$ do
        Compute $w^*(W_{st}, W_{skt}, W_{bt}, \alpha(b,s), \theta)$;
        Update surface water supply
            $W_{st} \leftarrow W_{st} - w^*$;
            $W_{skt} \leftarrow W_{skt} - w^*$;
            $W_{bt} \leftarrow W_{bt} + \alpha(s,b)w^*$;
        Adjust volume, net trade, and distance moments;
    Run trade flow regression and compute residual variance.
    Result: $\hat{M}(\theta, \varepsilon, \sigma)$
```

There are 17 target moments to match by simulated method of moments. The moments are shown in Table 16 and include:

1. Average (across years) trade volumes by transaction type: AgToAg, CityToAg, CityToCity, AgToCity, isRight, ProjectExport, CrossDelta.

---

[36] We randomly permute bilateral pairs and in order σ_{sbt} we enact trade. We will use

[37] For computational feasibility, we approximate this optimal trade quantity w^* by the procedure described in Section B.4

2. Average distance of trades weighted by trade quantity.
3. Net trade (imports - exports) by hydrologic region.
4. Residual variance of regression specification in Column (2) of Table 4, estimated on simulated trade flows.

The first 7 moments correspond to parameters τ_1-τ_7, average distance to parameter τ_8, the 8 regional net trade moments to parameters ψ_r, and the last residual variance moment to parameter ν.

B.3 Simulated Method of Moments Estimation

I estimate parameters $\theta = (\tau, \psi, \nu)$ by simulated method of moments matching the moments as described above. The objective function for our estimation is computed as follows.

1. Draw $R = 100$ vectors of errors and permutations of orders across pairs. Let ε^r be one draw of the vector of errors ε^r_{sbt} and σ^r the permutation of pairs where σ^r_{sbt} is the index of the order in which trade is evaluated for (s, b) in t.
2. Choose some parameters θ'.
3. For each r, compute moments $\hat{M}^r(\theta) = \hat{M}^r(\theta', \varepsilon^r, \sigma^r)$. Let $\hat{M}(\theta')$ be the $K \times R$ matrix where row k and column r indicates the kth moment under draw r, $\hat{M}^r_k(\theta')$.
4. Compute average moment $\overline{M}(\theta') = \frac{1}{R}\sum_{r=1}^{R} \hat{M}^r(\theta')$.
5. Relative to observed moments M, compute percent error of average simulated moments: $\overline{e}(\theta') = \frac{\overline{M}(\theta') - M}{M}$.
6. Given weight matrix, W, compute total weighted error: $E(\theta') = \overline{e}(\theta')^T W \overline{e}(\theta')$.

The weight matrix W is the inverse variance-covariance matrix of estimated moments which I estimate with a two-step procedure as in Hansen & West (2002).

1. Numerically minimize the objective function in step (6) above letting the weight matrix be the identity matrix to get the first set of parameter estimates:

$$\theta^1 = \arg\min_{\theta} \overline{e}(\theta)^T \mathbf{I} \overline{e}(\theta)$$

2. Estimate the weight matrix by the variance-covariance of moments across simulated shocks/orders:

$$\hat{W}(\theta^1) = \left(\frac{1}{R}\hat{M}(\theta^1)\hat{M}(\theta^1)^T\right)^{-1}$$

3. Compute final parameter estimates $\hat{\theta}$ by minimizing:

$$\hat{\theta} = \arg\min_{\theta} \overline{e}(\theta)^T \hat{W}(\theta^1) \overline{e}(\theta)$$

B.4 Approximating optimal bilateral trade

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:

$$\widetilde{MV}_{it}(W) = 2a_{it}W + b_{it} \tag{37}$$

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 $W_{it}^{max} = \arg\max_W V_{it}(W)$. 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:

$$MV_{it}(W_{it}) = 2a_{it}W_{it} + b_{it} \tag{38}$$

$$0 = 2a_{it}W_{it}^{max} + b_{it}. \tag{39}$$

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.

$$\widetilde{MV}_{it}(W) = \begin{cases} 2a_{it}^{L}W + b_{it}^{L} & W \leq W_{it} \\ 2a_{it}^{H}W + b_{it}^{H} & W > W_{it} \end{cases} \tag{40}$$

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

$$MV_{it}(W_{it}) = 2a_{it}^{H}W_{it} + b_{it}^{H} = 2a_{it}^{L}W_{it} + b_{it}^{L} \tag{41}$$

$$0 = 2a_{it}^{H}W_{it}^{max} + b_{it}^{H} \tag{42}$$

$$MV_{it}\left(\frac{W_{it}}{4}\right) = 2a_{it}^{L}\frac{W_{it}}{4} + b_{it}^{L} \tag{43}$$

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.

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

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.5 Water Supply Source 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 Details on Counterfactuals

C.1 Changing Constraints across Counterfactuals

Many of the counterfactuals I consider will change the trade adjustments, $\alpha(s,b)$, made to satisfy current regulations or hydrological feasibility. I will describe two modifications I make to $\alpha(s,b)$ that will be used across the many counterfactuals described more explicitly in the following section.

Delta constraint: Because of the salinity and endangered fish species concerns in the Delta, there are restrictions on transfers that require carriage water as additional outflow. In Equation 36, the way Delta constraints enter the trade adjustment function is through carriage water parameter CW_{sb}, which is the share of water that must be left for freshwater outflow. California is considering building the Delta conveyance project, which is a pipeline that would eliminate this constraint. In counterfactuals where the Delta constraint is eliminated, I set $CW_{sb} = 0$ so that the only potential constraints on trade have to do with return flow management.

Return flow constraint: The main counterfactuals I consider regarding return flow management vary the specificity of return flow internalization. In Equation 36, the tradable quantity is adjusted by the specific consumptive share of the seller, κ_{st}. The counterfactuals I consider instead let this adjustment be some constant $\kappa_{st} = \kappa$, independent of the specific seller. If the counterfactual mentions return flow constraints being eliminated entirely, this means that $\kappa = 1$.

C.2 Description of each Counterfactual

In this section, I specify how I compute each counterfactual.

Baseline: Transaction costs $\tau_{sbt}(\hat{\theta})$ as estimated and $\alpha(s,b)$ as in Equation 36.

No RF Cost: Set cost parameter $\tau_6 = 0$ and $\tau_5 = \hat{\tau}_5 - \hat{\tau}_6$.

No RF Constraint: In $\alpha(s,b)$ eliminate return flow adjustments by setting $\kappa_{st} = 1$.

No Delta Cost: Set cost parameter $\tau_7 = 0$.

No Delta Constraint: In $\alpha(s,b)$, eliminate Delta constraints with carriage water $CW_{sb} = 0$.

No Delta Friction: Combine *No Delta Cost* and *No Delta Friction*.

No Delta Friction, No RF Cost: Combine *No RF Cost* and *No Delta Friction*.

No Right Cost: Set cost parameter $\tau_5 = \hat{\tau}_6$.

No Right/RF Cost: Set cost parameters $\tau_5 = \tau_6 = 0$.

No Delta Friction, No Right/RF Cost: Combine *No Delta Friction* and *No Right/RF Cost*.

No AgToCity Friction: Set cost parameter $\tau_4 = 0$.

No AgToCity, No Delta Friction, No RF Cost: Combine *No AgToCity* and *No Delta Friction, No RF Cost*.

No AgToCity, No Delta Friction, No Right/RF Cost: Combine *No AgToCity* and *No Delta Friction, No Right/RF Cost*.

No Distance Cost: Set $\tau_8 = 0$, removing per mile frictions.

Baseline, Costly RF Information: This is the same as *Baseline*, but makes clear that return flow measurement costs are being paid to learn κ_{st} in the $\alpha(s, b)$ function.

Baseline, Perfect RF Information: This is the same as *No RF Cost*, but makes clear that return flow measurement costs are being eliminated while still having perfect information about κ_{st}.

Baseline, RF Adjustment Share: This counterfactual as the same transaction costs as *No RF Cost*, setting $\tau_6 = 0$ and $\tau_5 = \hat{\tau}_5 - \hat{\tau}_6$, but these costs are eliminated by ignoring seller specific consumptive shares and fixing $\kappa_{st} = \kappa$ for all sellers. I estimate counterfactuals for $\kappa \in [0.5, 1]$ in 0.02 intervals.

Baseline, No RF Info, No Harm: This counterfactual is from the set of *Baseline, RF Adjustment Share* counterfactuals. I let $\kappa = 0.72$ which is the largest share possible without harming any user or environmental constraint.

No Delta Friction, Costly RF Information: This is the same as *No Delta Friction*, but makes clear that return flow measurement costs are being paid to learn κ_{st} in the $\alpha(s, b)$ function.

No Delta Friction, Perfect RF Information: This is the same as *No Delta Friction, No RF Cost*, but makes clear that return flow measurement costs are being eliminated while still having perfect information about κ_{st}.

No Delta Friction, RF Adjustment Share: This counterfactual removes Delta constraints, $CW_{sb} = 0$ and has the same transaction costs as *No Delta Friction, No RF Cost*, setting $\tau_7 = 0$, $\tau_6 = 0$ and $\tau_5 = \hat{\tau}_5 - \hat{\tau}_6$, but eliminates RF measurement costs by ignoring seller specific consumptive shares and fixing $\kappa_{st} = \kappa$ for all sellers. I estimate counterfactuals for $\kappa \in [0.5, 1]$ in 0.02 intervals.

No Delta Friction, No RF Info, No Harm: This counterfactual is from the set of *No Delta Friction, RF Adjustment Share* counterfactuals. I let $\kappa = 0.70$ which is the largest share possible without harming any user or environmental constraint.

No Delta Friction, No Right, Costly RF Information: This counterfactual removes Delta constraints, $CW_{sb} = 0$ and has transaction costs $\tau_5 = \hat{\tau}_6$ and $\tau_7 = 0$. Return flow measurement costs are being paid to learn κ_{st} in the $\alpha(s, b)$ function.

No Delta Friction, No Right, Perfect RF Information: This counterfactual removes Delta constraints, $CW_{sb} = 0$ and has transaction costs $\tau_5 = 0$, $\tau_6 = 0$, and $\tau_7 = 0$. Return flow measurement costs are eliminated while still having perfect information about κ_{st}.

No Delta Friction, No Right, RF Adjustment Share: This counterfactual removes Delta constraints, $CW_{sb} = 0$ and has transaction costs $\tau_5 = 0$, $\tau_6 = 0$, and $\tau_7 = 0$. Return flow measurement costs are eliminated by ignoring seller specific consumptive shares and fixing $\kappa_{st} = \kappa$ for all sellers. I estimate counterfactuals for $\kappa \in [0.5, 1]$ in 0.02 intervals.

No Delta Friction, No Right, No RF Info, No Harm: This counterfactual is from the set of *No Delta Friction, No Right, RF Adjustment Share* counterfactuals. I let $\kappa = 0.70$ which is the largest share possible without harming any user or environmental constraint.

No AgToCity, No Delta Friction, Costly RF Information: This counterfactual removes Delta constraints, $CW_{sb} = 0$ and has transaction costs $\tau_4 = 0$ and $\tau_7 = 0$. Return flow measurement costs are being paid to learn κ_{st} in the $\alpha(s, b)$ function.

No AgToCity, No Delta Friction, Perfect RF Information: This counterfactual removes Delta constraints, $CW_{sb} = 0$ and has transaction costs $\tau_4 = 0$, $\tau_5 = \hat{\tau}_5 - \hat{\tau}_6$, $\tau_6 = 0$, and $\tau_7 = 0$. Return flow measurement costs are eliminated while still having perfect information about κ_{st}.

No AgToCity, No Delta Friction, RF Adjustment Share: This counterfactual removes Delta constraints, $CW_{sb} = 0$ and has transaction costs $\tau_4 = 0$, $\tau_5 = \hat{\tau}_5 - \hat{\tau}_6$, $\tau_6 = 0$, and $\tau_7 = 0$. Return flow measurement costs are eliminated by ignoring seller specific consumptive shares and fixing $\kappa_{st} = \kappa$ for all sellers. I estimate counterfactuals for $\kappa \in [0.5, 1]$ in 0.02 intervals.

No AgToCity, No Delta Friction, No RF Info, No Harm: This counterfactual is from the set of *No AgToCity, No Delta Friction, RF Adjustment Share* counterfactuals. I let $\kappa = 0.70$ which is the largest share possible without harming any user or environmental constraint.

No AgToCity, No Delta Friction, No Right, Costly RF Information: This counterfactual removes Delta constraints, $CW_{sb} = 0$ and has transaction costs $\tau_4 = 0$, $\tau_5 = \hat{\tau}_6$ and $\tau_7 = 0$. Return flow measurement costs are being paid to learn κ_{st} in the $\alpha(s, b)$ function.

No AgToCity, No Delta Friction, No Right, Perfect RF Information: This counterfactual removes Delta constraints, $CW_{sb} = 0$ and has transaction costs $\tau_4 = 0$, $\tau_5 = 0$, $\tau_6 = 0$, and $\tau_7 = 0$. Return flow measurement costs are eliminated while still having perfect information about κ_{st}.

No AgToCity, No Delta Friction, No Right, RF Adjustment Share: This counterfactual removes Delta constraints, $CW_{sb} = 0$ and has transaction costs $\tau_4 = 0$, $\tau_5 = 0$, $\tau_6 = 0$, and $\tau_7 = 0$. Return flow measurement costs are eliminated by ignoring seller specific consumptive shares and fixing $\kappa_{st} = \kappa$ for all sellers. I estimate counterfactuals for $\kappa \in [0.5, 1]$ in 0.02 intervals.

No AgToCity, No Delta Friction, No Right, No RF Info, No Harm: This counterfactual is from the set of *No Delta Friction, No Right, RF Adjustment Share* counterfactuals. I let $\kappa = 0.70$ which is the largest share possible without harming any user or environmental constraint.

D 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 × Use)-to-(DAUCO × 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:

$$S_{ikt}(G) = \sum_{h} \sum_{j \in G, j \neq i} S_{ikjht} \tag{44}$$

$$D_{jht}(G) = \sum_{k} \sum_{i \in G, i \neq j} S_{ikjht} \tag{45}$$

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

$$S_{ikjht} = \lambda_G(i,k,j,h) S_{ikt}(G) \tag{46}$$

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:

$$\begin{aligned}
&\arg\min_{\lambda_G} \sum_{j \in G} \sum_{h} \Big(D_{jht}(G) - \sum_{i \in G, i \neq j} \sum_{k} \lambda_G(i,k,j,h) S_{ikt} \Big)^2 && (47)\\
&\text{s.t.} \quad \sum_{j \in G, j \neq i} \sum_{h} \lambda_G(i,k,j,h) = 1, \text{ for all } i \in G \text{ and } k. && (48)\\
&\lambda_G(i,k,j,h) \geq 0. && (49)
\end{aligned}$$

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:

$$N_G^S = \sum_{i \in G} \sum_{k} \mathbf{1}\Big[\sum_{t} S_{ikt}(G) > 0 \Big] \tag{50}$$

$$N_G^D = \sum_{j \in G} \sum_{h} \mathbf{1}\Big[\sum_{t} D_{jht}(G) > 0 \Big] \tag{51}$$

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 12 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.

E Data Construction

This section details key variables, data source, missing/error correction, and sample restriction choices.

E.1 Crop and Water Use Data

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.

E.2 Data for Utility Water Demand Estimation

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.

E.3 Groundwater Depth Data

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.

E.4 Trade Data

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.

E.5 Hydrological Network Data

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.

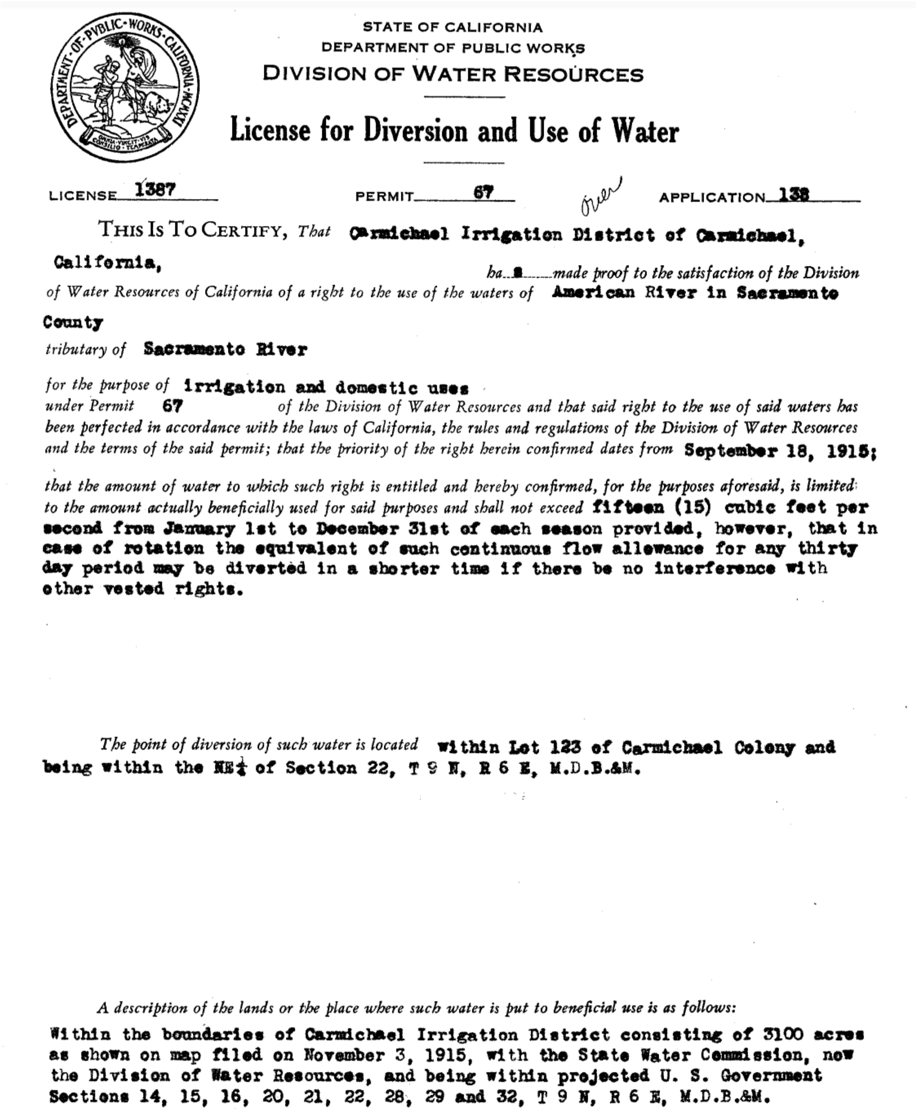
1. Constructing the Natural Flow Network: Flowline shapefiles from the NHDPlusV2 dataset were loaded to capture natural river connections between nodes, identified by coordinates.
2. Establishing DAUCO Nodes: I linked flowline coordinates to DAUCOs by spatial matching. Using the order of flowline segments, 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.

F Appendix Figures



STATE OF CALIFORNIA
DEPARTMENT OF PUBLIC WORKS
DIVISION OF WATER RESOURCES

License for Diversion and Use of Water

LICENSE **1387** PERMIT **67** over APPLICATION **138**

THIS IS TO CERTIFY, *That* **Carmichael Irrigation District of Carmichael, California,** *ha***s** *made proof to the satisfaction of the Division of Water Resources of California of a right to the use of the waters of* **American River in Sacramento County**

tributary of **Sacramento River**

for the purpose of **irrigation and domestic uses**
under Permit **67** *of the Division of Water Resources and that said right to the use of said waters has been perfected in accordance with the laws of California, the rules and regulations of the Division of Water Resources and the terms of the said permit; that the priority of the right herein confirmed dates from* **September 18, 1915;**

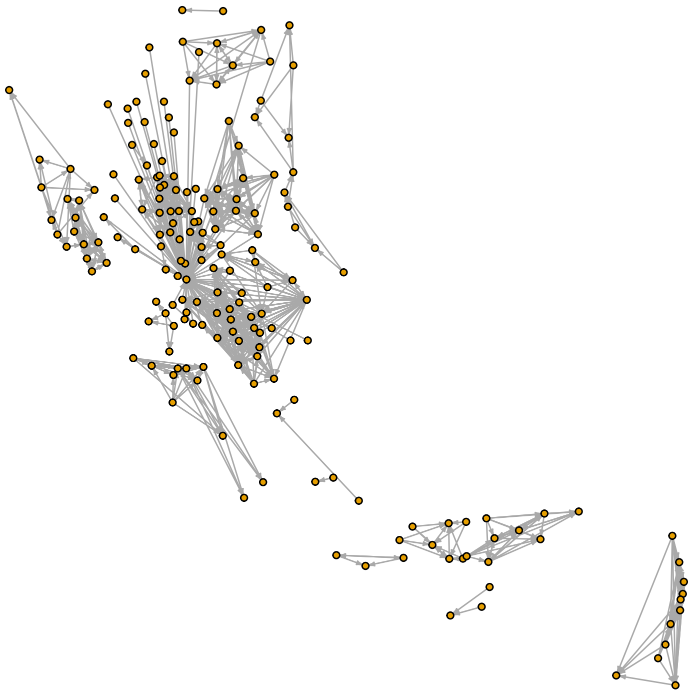
that the amount of water to which such right is entitled and hereby confirmed, for the purposes aforesaid, is limited to the amount actually beneficially used for said purposes and shall not exceed **fifteen (15) cubic feet per second from January 1st to December 31st of each season provided, however, that in case of rotation the equivalent of such continuous flow allowance for any thirty day period may be diverted in a shorter time if there be no interference with other vested rights.**

The point of diversion of such water is located **within Lot 123 of Carmichael Colony and being within the NE¼ of Section 22, T 9 N, R 6 E, M.D.B.&M.**

A description of the lands or the place where such water is put to beneficial use is as follows:
Within the boundaries of Carmichael Irrigation District consisting of 3100 acres as shown on map filed on November 3, 1915, with the State Water Commission, now the Division of Water Resources, and being within projected U. S. Government Sections 14, 15, 16, 20, 21, 22, 28, 29 and 32, T 9 N, R 6 E, M.D.B.&M.

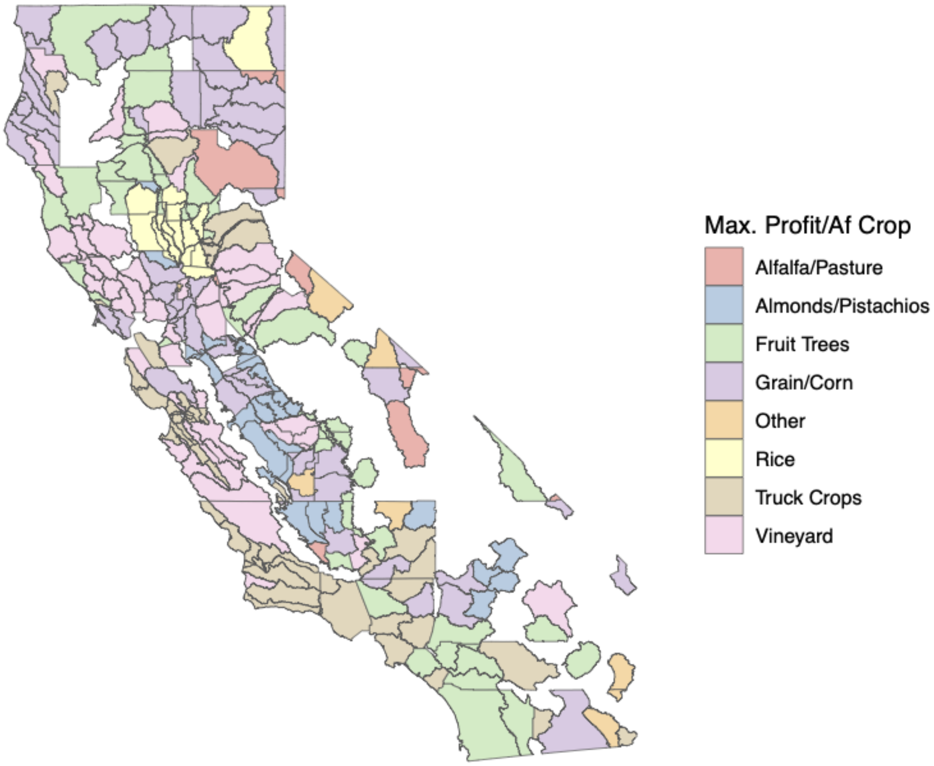
Figure 11: Example of Right to Surface Water

Figure 12: Return Flow Network



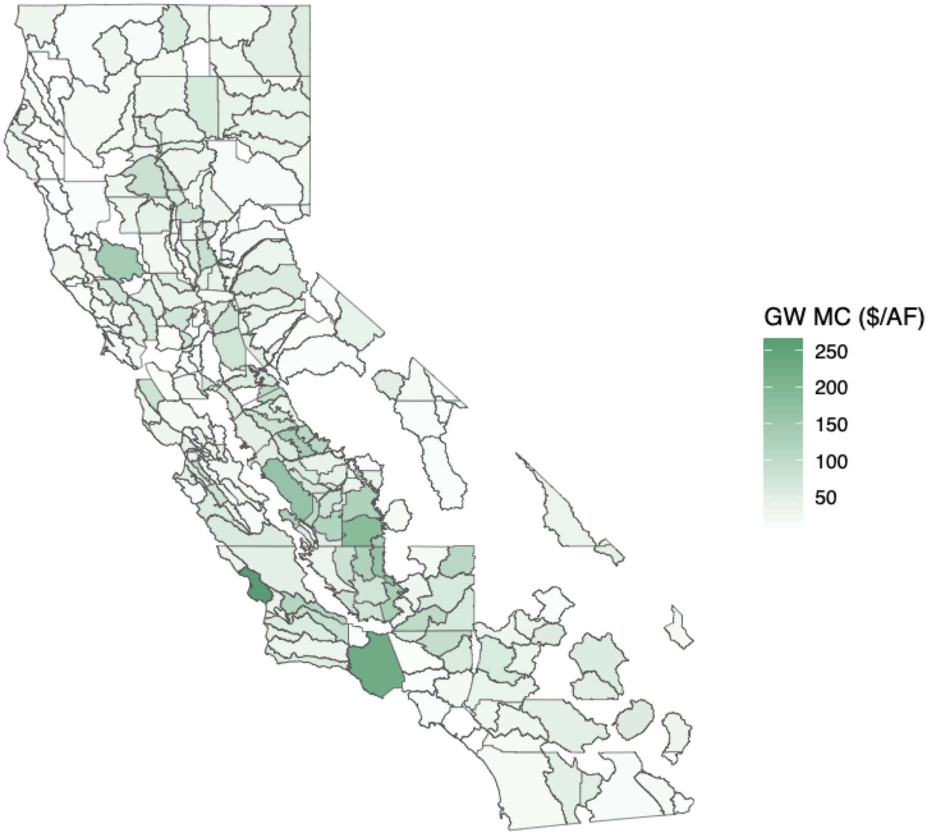
Notes: Figure shows the network of return flow contributions between DAUCOs. An arrow indicates that some share of return flow is contributed from the origin to the destination DAUCO. These edges and their associated weights are estimated according to the procedure described in Section D.

Figure 13: Profit/af Maximizing Crops



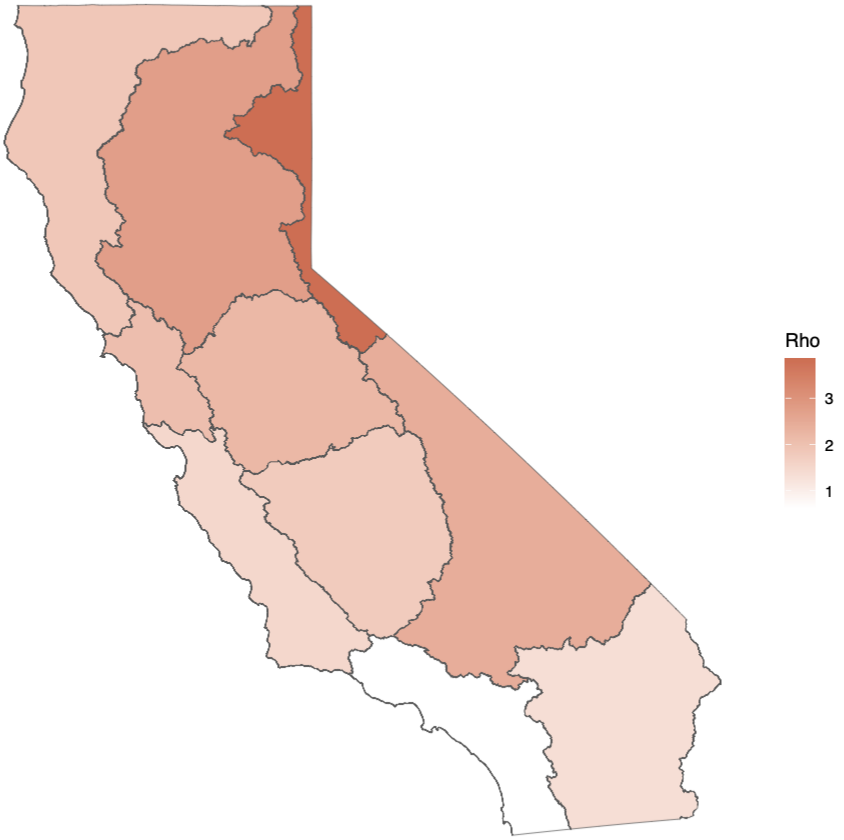
Notes: Figure depicts for each DAUCO the crop with the largest average profit per acre-foot. Profit parameters are estimated as in Section 5. Profits are averaged over years 2005-2015.

Figure 14: Marginal Cost of GW



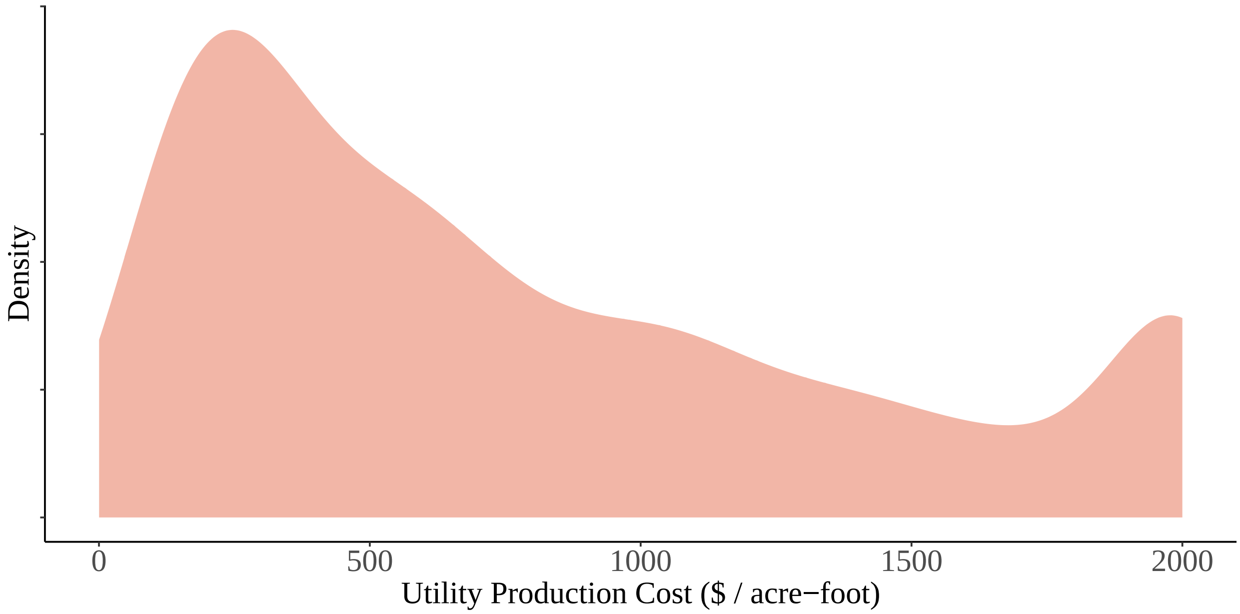
Notes: Figure depicts the estimated average marginal cost of groundwater, which is equivalent to agricultural marginal willingness-to-apy, for each DAUCO. Marginal costs are averaged over years 2005-2015 and estimated as specified in Section 5.

Figure 15: Pumping Efficiency (kWh / af × foot)



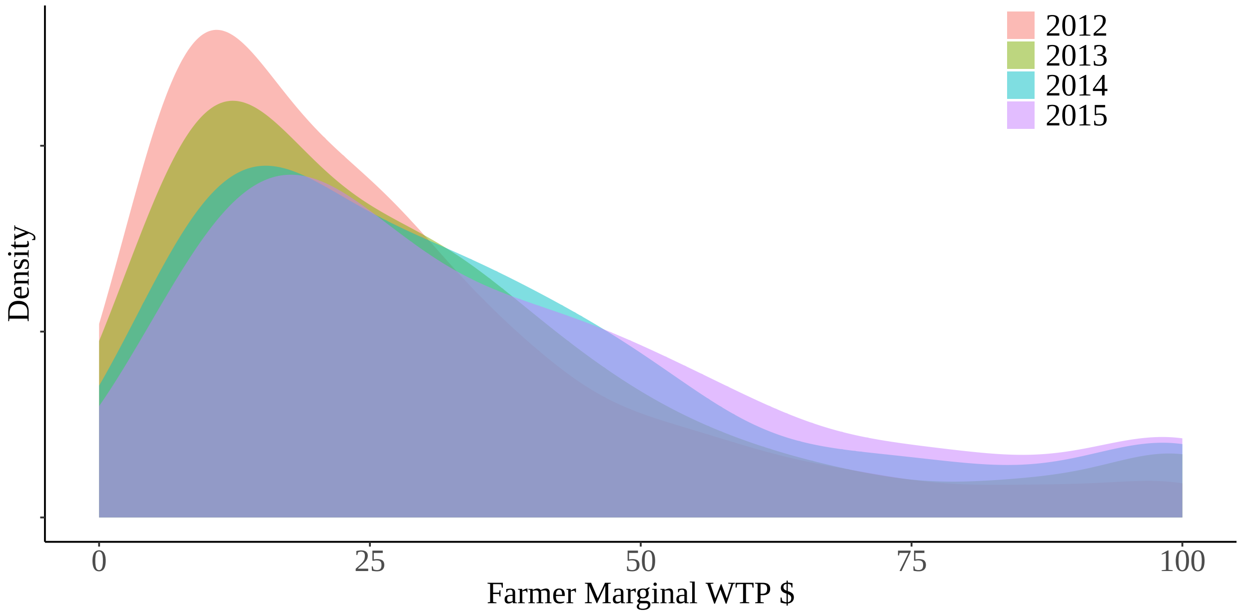
Notes: Figure depicts the estimated regional pumping efficieny parameters which are in kWh per acre-foot per foot height pumped. Pumping efficiency ρ is as estimated in Section 5.

Figure 16: Utility Production Costs



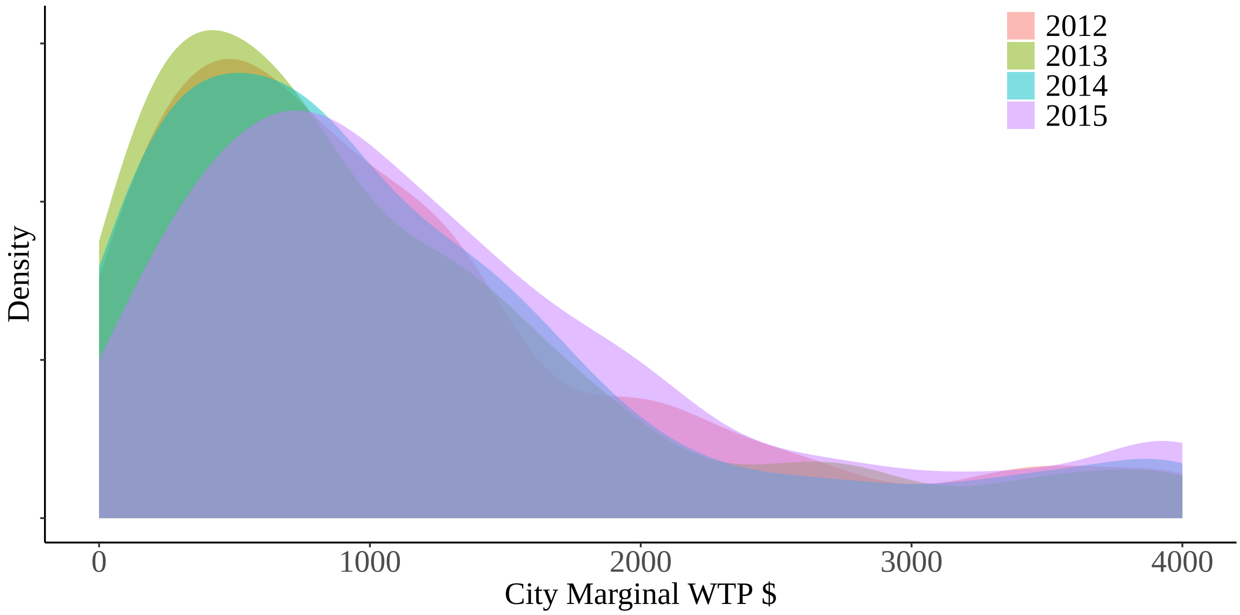
Notes: Figures depicts the distribution of average unit production costs for urban utilities. These costs are reported by the utilities and the distribution includes reports from 2016-2022.

Figure 17: Agricultural Marginal WTP by Year



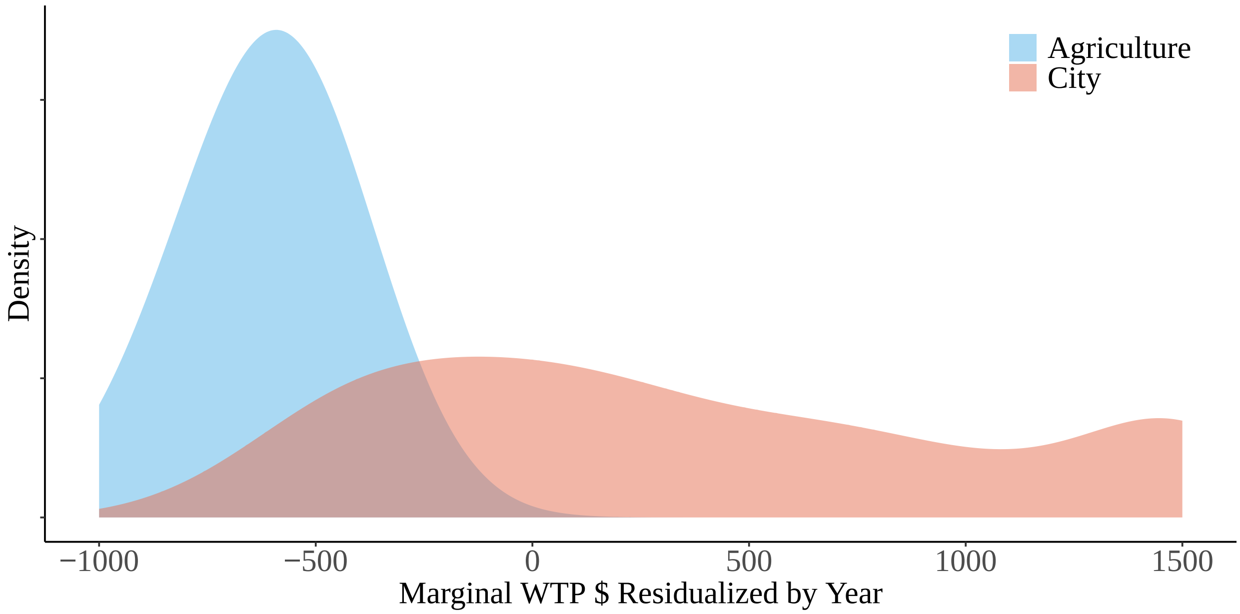
Notes: Figure depicts the distribution of agricultural marginal willingness-to-pay across years 2012-2015. Marginal WTP is in $/af.

Figure 18: City Marginal WTP by Year



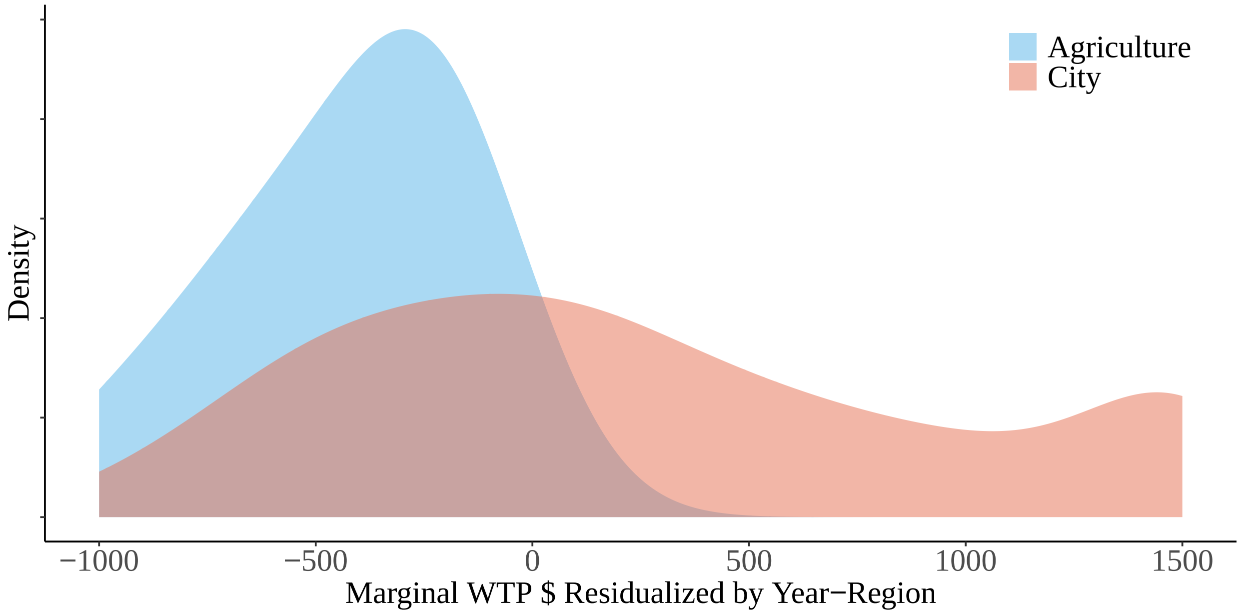
Notes: Figure depicts the distribution of urban marginal willingness-to-pay across years 2012-2015. Marginal WTP is in $/af.

Figure 19: Marginal WTP by Use



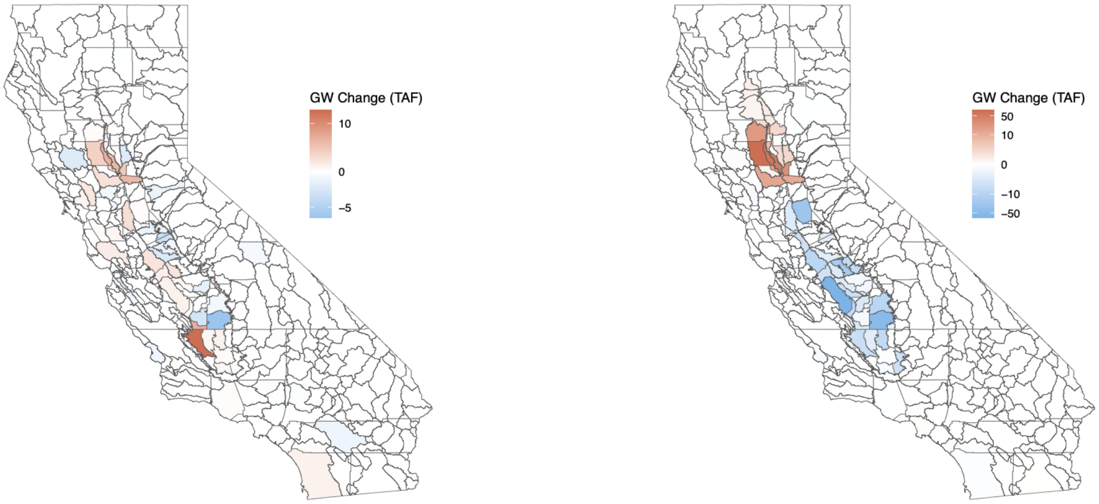
Notes: Figure depicts the distribution of agricultural and urban marginal willingness-to-pay across years 2012-2015. Marginal WTP is in $/af and is residualized by year.

Figure 20: Marginal WTP by Use



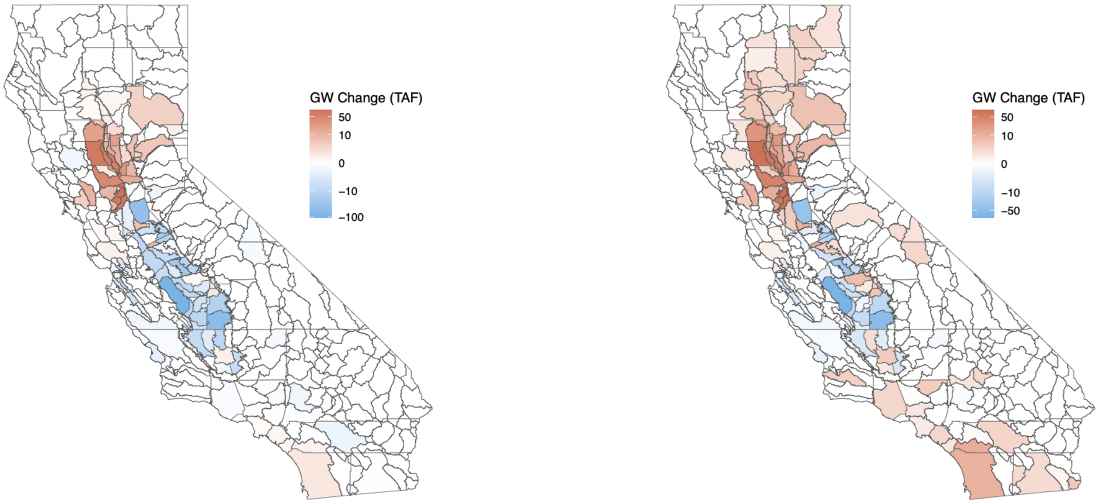
Notes: Figure depicts the distribution of agricultural and urban marginal willingness-to-pay across years 2012-2015. Marginal WTP is in $/af and is residualized by year-region.

Figure 21: Counterfactual Groundwater Pumping Changes



(a) No RF Cost

(b) No Delta Friction

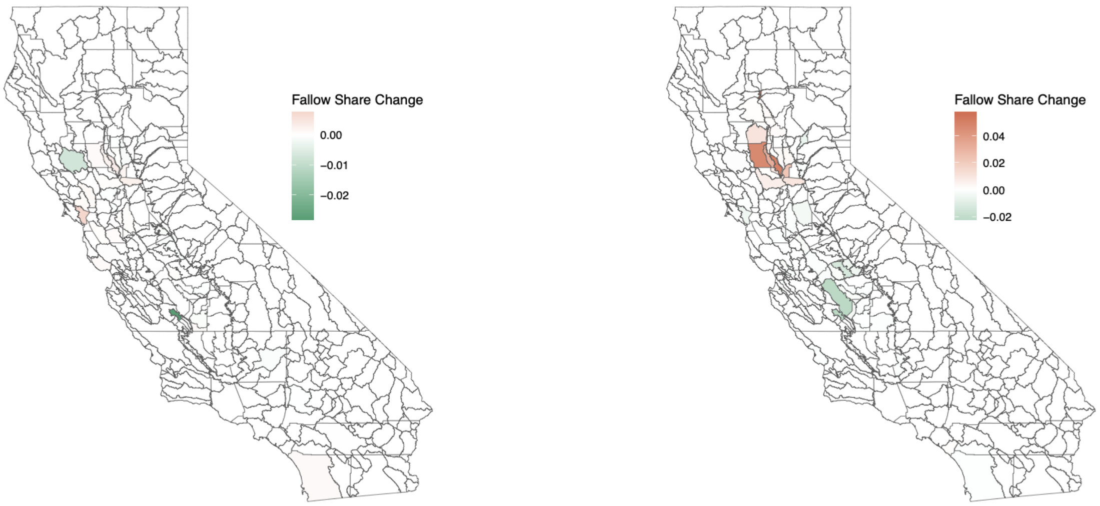


(c) No Right/RF, No Delta Friction

(d) No AgToCity, No Right/RF, No Delta Friction

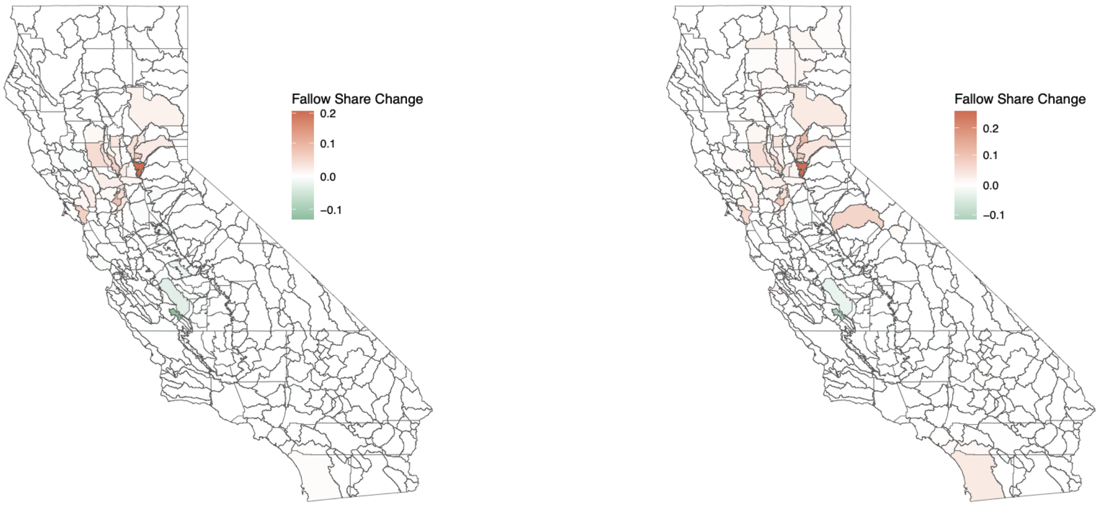
Notes: Four panels depict the change in groundwater pumping across DAUCOs under the counterfactual indicated in the subcaption. Counterfactual pumping changes are averaged over years 2012-2015.

Figure 22: Counterfactual Percentage Point Changes in Fallowing Share



(a) No RF Cost

(b) No Delta Friction

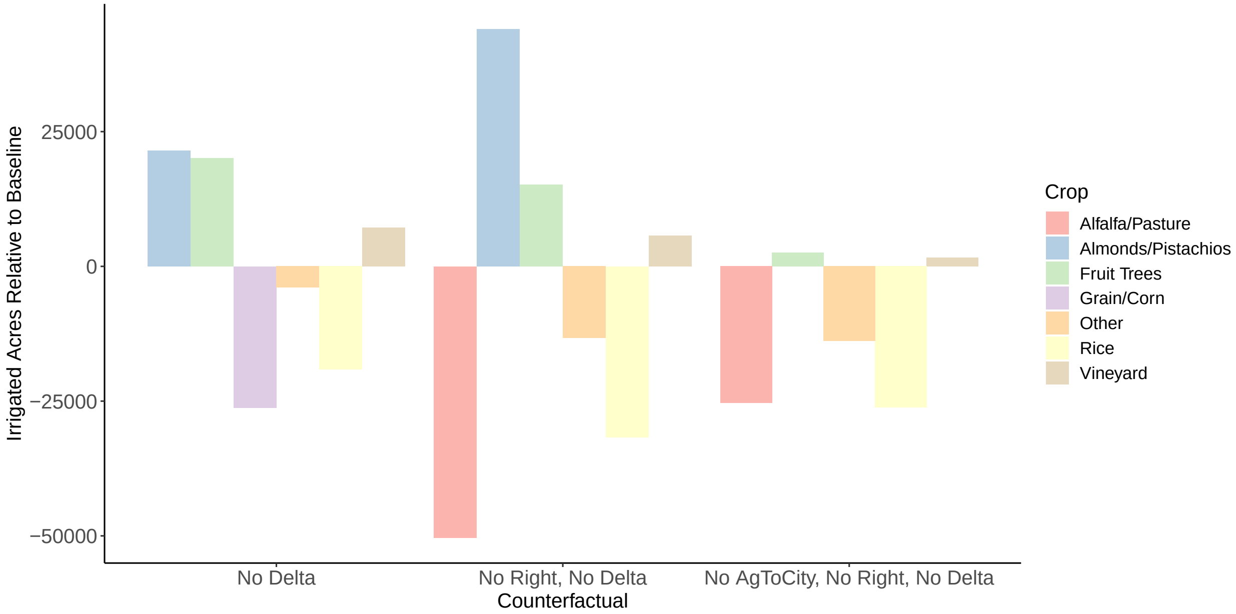


(c) No Right/RF, No Delta Friction

(d) No AgToCity, No Right/RF, No Delta Friction

Notes: Four panels depict the percentage point change in fallowing share across DAUCOs under the counterfactual indicated in the subcaption. Counterfactual fallowing shares are averaged over years 2012-2015.

Figure 23: Largest Crop Switching by Selected Counterfactuals



Notes: Figure shows the change in irrigated acres for the three most positively and negatively affected crops across three counterfactuals corresponding to removing Delta frictions, additionally removing right verification costs, then additionally removing AgToCity frictions. Changes are averaged over all years 2012-2015.

G Appendix Tables

Table 10: Trade Friction Regression

	$\log(s_{odt}) - \log(s_{oot})$ (1)	(2)
Constant	-8.595***	-8.443***
	(0.1815)	(0.1619)
CityToAg	-0.0781	0.7328***
	(0.1269)	(0.1968)
CityToCity	-0.1447	-0.1903
	(0.1267)	(0.1125)
AgToCity	-0.3299***	-1.061***
	(0.0264)	(0.1249)
AgCommunityVotes	-0.5382***	-0.5502***
	(0.1381)	(0.1288)
isRight	-1.688***	-1.676***
	(0.1169)	(0.1136)
ProjectExport	-0.4827***	-0.4525***
	(0.0365)	(0.0369)
CrossDelta	-0.5152***	-0.4420***
	(0.0547)	(0.0591)
Distance (100 miles)	-0.0267***	-0.0311***
	(0.0077)	(0.0072)
GWDepthGap (10ft)		
MarginalGain ($1k)		1.335***
		(0.2093)
Observations	11,932	11,932
R^2	0.24034	0.29115
Adjusted R^2	0.23894	0.28978

Table 11: 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 5.1 and 5.2

Table 12: 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.

Table 13: 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.

Table 14: Urban Demand Estimation

	LogQuantity		Price ($100)	LogQuantity		Price ($100)
	IV	OLS	First-Stage	IV	OLS	First-Stage
Price ($100)	-0.0094**	-0.0023***		-0.0233***	-0.0518***	
	(0.0043)	(0.0008)		(0.0039)	(0.0107)	
LogRain	-0.0018	-0.0032	0.1885	0.0192	0.0393***	-1.122**
	(0.0253)	(0.0151)	(2.140)	(0.0153)	(0.0104)	(0.4653)
LogHouseholds	0.7905***	0.7952***	-0.2895	1.031***	0.9821***	3.955***
	(0.0808)	(0.0819)	(1.133)	(0.0258)	(0.0099)	(0.8775)
LogVolOwn			-1.024***			-0.7255***
			(0.2200)			(0.0816)
LogIncome				0.0681**	0.0253	-0.1790
				(0.0256)	(0.0226)	(0.8341)
LogLotSize				-0.0930	0.0650	-8.979*
				(0.0992)	(0.0501)	(4.529)
Observations	1,998	1,998	1,998	1,998	1,998	1,998
F-test (1st stage), Price			46.332			58.310
R^2	0.99875	0.99900	0.93286	0.95038	0.96908	0.37839
Within R^2	0.58473	0.66782	0.01465	0.94054	0.96294	0.07053
Year-HydroRegion fixed effects	✓	✓	✓	✓	✓	✓
UtilityID fixed effects	✓	✓	✓			

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.

Table 15: Urban Demand Estimation: Log-Log Specification

	LogQuantity		LogPrice	LogQuantity		LogPrice
	IV	OLS	First-Stage	IV	OLS	First-Stage
LogPrice	-0.3383**	-0.0273**		-0.4230***	-0.1692***	
	(0.1413)	(0.0132)		(0.0630)	(0.0178)	
LogRain	-0.0050	-0.0038	-0.0042	0.0143	0.0328***	-0.0736***
	(0.0296)	(0.0142)	(0.0755)	(0.0143)	(0.0102)	(0.0241)
LogHouseholds	0.7989***	0.7968***	0.0166	1.040***	0.9967***	0.2379***
	(0.0829)	(0.0820)	(0.0518)	(0.0228)	(0.0102)	(0.0395)
LogVolOwn			-0.0285***			-0.0401***
			(0.0064)			(0.0036)
LogIncome				0.0709***	0.0362	-0.0032
				(0.0254)	(0.0236)	(0.0433)
LogLotSize				0.0820	0.0988**	-0.0818
				(0.0635)	(0.0475)	(0.1104)
Observations	1,998	1,998	1,998	1,998	1,998	1,998
F-test (1st stage), LogPrice			15.488			99.423
R^2	0.99791	0.99898	0.94366	0.96386	0.97051	0.43281
Within R^2	0.30599	0.66234	0.00381	0.95669	0.96466	0.08178
Year-HydroRegion fixed effects	✓	✓	✓	✓	✓	✓
UtilityID fixed effects	✓	✓	✓			

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.

Table 16: Estimated Moments

Moment	Target	Estimate		Target	Estimate
Avg. Trade Volume (TAF)			*Avg. Net Trade by Region (TAF)*		
AgToAg	305.5	286.7	Central Coast	4.3	4.3
CityToAg	7.1	7.4	Colorado River	3	2.9
CityToCity	3.8	3.9	Sacramento River	-474.2	-435.9
AgToCity	18.4	22.8	San Francisco Bay	20	19.5
IsRight	13.8	15	San Joaquin River	-172	-170.1
ProjectExport	20.6	19.1	South Coast	6.7	6.6
CrossDelta	121.2	115.1	South Lahontan	13.4	11.8
			Tulare Lake	598.8	560.9
Other					
AvgDistance (miles)	131.49	120.35			
Residual Variance	4.17	4.42			

Notes: The table indicates the 17 moments I compute after simulating trade at the optimal parameters in Table 7. I report the target moment I observe in the data and the estimate.

Table 17: Crop Changes by Counterfactual: First Set

Counterfactual		Alfalfa	Almonds/Pistachios	Citrus/Subtropical	Corn	Cotton	Cucurbits	Dry Beans	Grain	Onion/Garlic
No AgToCity Friction	Dry	-0.64	-0.67	-0.46	0.03	-1.43	0.09	0.01	0.52	-0.13
	Normal	-0.49	-0.48	-0.39	0.06	-0.14	0.07	0.11	0.37	-0.06
	Wet	-0.33	-0.31	-0.31	0.07	-0.11	0.17	0.1	0.33	-0.02
No Delta Constraint	Dry	0.21	0.36	0.31	-0.06	0.21	-0.14	-0.36	-0.6	0.24
	Normal	0.08	0.3	0.09	-0.02	0.06	-0.07	-0.08	-0.13	0.04
	Wet	0.03	0.22	0.04	-0.03	0.04	-0.03	-0.04	-0.05	0.01
No Delta Cost	Dry	0.03	-0.02	0.11	-0.06	0.09	-0.06	-0.27	-0.17	0.09
	Normal	-0.01	0.18	0.04	-0.02	0.04	-0.06	-0.04	-0.02	-0.01
	Wet	0	0.18	0.04	-0.04	0.03	-0.02	-0.04	-0.02	0
No Distance Cost	Dry	-0.39	0.25	1.58	0.02	-2.34	-0.19	0.04	-0.6	-0.16
	Normal	0.02	0	1.85	-0.09	-0.44	-0.53	-0.25	-0.71	-0.36
	Wet	0.18	0.06	0.42	0.09	-0.19	0	0.3	-0.39	0.02
No Frictions	Dry	-3.86	-0.28	3.76	-2.21	-0.49	-3.52	-3.74	-0.19	-0.46
	Normal	-3.77	-3.31	2.78	-0.81	0.67	-2.57	-1.59	1.1	-1.42
	Wet	-1.13	-2.18	3.11	-0.2	0.26	0.25	0.51	-0.18	0.06
No RF Constraint.	Dry	0.03	0.03	0.05	0	0.02	-0.01	-0.01	-0.07	0
	Normal	0	0.01	0.01	0	0.02	-0.01	0	-0.01	-0.01
	Wet	0	-0.01	0.01	0	0	0	0	-0.01	-0.01
No RF Cost	Dry	0.06	0.04	0.11	0	-0.31	-0.03	-0.04	-0.17	0
	Normal	0.02	0.08	0.05	-0.01	0.02	-0.03	0	-0.03	-0.06
	Wet	0.01	0.09	0.03	0	-0.02	0	0.01	-0.02	-0.04
No RF Cost, No Delta Friction	Dry	0.48	0.79	0.78	-0.19	0.27	-0.39	-0.85	-1.14	0.39
	Normal	0.1	0.16	0.32	-0.09	0.31	-0.13	-0.18	-0.29	-0.05
	Wet	0.09	-0.33	0.17	-0.09	0.05	0.07	-0.06	-0.13	-0.05
No Right/RF/Delta Cost	Dry	0.07	2.41	1.73	-0.31	-0.48	-1.14	-1.28	-1.65	0.51
	Normal	-0.87	0.36	0.84	0.55	0.61	-0.38	-0.44	-0.29	-0.36
	Wet	-0.56	-0.42	0.41	0.62	0.23	-0.13	-0.24	-0.04	-0.09

Notes: Table reports the statewide percent change in irrigated acres for each crop across counterfactuals and drought scenarios. This table contains the first half of crops alphabetically.

Table 18: Crop Changes by Counterfactual: Second Set

Counterfactual		Fresh Tomato	Other Deciduous	Other Field	Pasture	Potato	Processing Tomato	Rice	Safflower	Truck Crops	Vineyard
No AgToCity Friction	Dry	0.08	0.09	-0.07	-0.65	-0.01	-0.12	-0.51	0.09	0.08	-0.1
	Normal	0.04	0.32	-0.02	-1.06	0	-0.03	-0.16	0.14	0.04	-0.09
	Wet	0.08	0.15	-0.05	-1.06	0.11	-0.02	-0.25	0.17	0.05	-0.06
No Delta Constraint	Dry	-0.37	0.53	0.01	-0.16	-0.02	-0.31	-0.8	-0.04	-0.08	0.2
	Normal	-0.11	0.19	0.04	-0.37	-0.02	-0.08	-0.12	0.04	-0.03	0.09
	Wet	-0.05	0.12	0	-0.4	0	-0.07	-0.07	0.04	-0.02	0.01
No Delta Cost	Dry	-0.14	0.48	-0.04	-0.17	-0.01	-0.23	-0.71	-0.03	-0.03	0.08
	Normal	-0.06	0.26	0.03	-0.46	-0.01	-0.08	-0.18	0.07	-0.02	0.06
	Wet	-0.05	0.14	-0.01	-0.43	-0.01	-0.09	-0.14	0.08	-0.02	0.01
No Distance Cost	Dry	-0.3	-0.1	-0.07	1.18	-0.99	0.02	0.54	0.15	-0.74	0
	Normal	-0.67	0.01	-0.14	0.94	-1.01	-0.31	0.02	-0.33	-1.15	0.22
	Wet	0.15	0.08	-0.06	0.46	-0.32	-0.06	0.06	-0.1	-0.14	0.02
No Frictions	Dry	-3.72	-4.99	-1.88	-2.48	-5.78	-4.63	-13.66	1.92	-3.24	0.43
	Normal	-2.5	-6.8	-0.74	-1.67	-5.03	-2.97	-8.99	1.75	-2.84	1.12
	Wet	2.51	-6.16	-1.21	-1.46	-0.67	-2.47	-9.98	3.39	-1.11	1.02
No RF Constraint.	Dry	0	0.02	0.01	0.02	0	0	-0.01	0.01	-0.02	0.02
	Normal	0	0	0	0.02	0	0	0	0	-0.01	0.01
	Wet	0	0	0	0.04	0	0	0	0	0	0
No RF Cost	Dry	-0.01	0.22	0.01	0.15	-0.01	-0.03	-0.09	0.03	-0.04	0.03
	Normal	0.01	0.07	-0.01	0.05	0	-0.01	-0.01	-0.02	-0.03	0.02
	Wet	0.02	0.01	-0.02	-0.08	0	-0.01	-0.02	0.02	-0.01	0.02
No RF Cost, No Delta Friction	Dry	-0.69	0.52	-0.06	0.06	-0.06	-0.67	-2.08	-0.07	-0.28	0.33
	Normal	-0.26	0.71	0.08	-0.06	-0.04	-0.23	-0.5	0.03	-0.15	0.23
	Wet	-0.13	0.64	-0.06	0.35	-0.01	-0.21	-0.33	0.13	-0.07	0.06
No Right/RF/Delta Cost	Dry	-1.64	0.32	-0.12	-1.47	-0.62	-1.47	-3.5	1.57	-0.65	0.33
	Normal	-0.7	0.28	0.2	-0.78	-0.42	-0.66	-1.26	1.28	-0.31	0.64
	Wet	-0.38	-0.12	-0.02	-0.69	-0.35	-0.57	-0.87	1.21	-0.07	0.05

Notes: Table reports the statewide percent change in irrigated acres for each crop across counterfactuals and drought scenarios. This table contains the second half of crops alphabetically.

Table 19: Counterfactual Results

Counterfactual		Trade Volume (TAF)	Net Gain ($M)	Cost ($M)	City Surplus ($M)	Ag. Surplus ($M)	Fallowing %	Pumping %
	Dry	135	3.6	34	0.2	37.3	0.13	0.2
No Delta Cost	Normal	104	2.4	24.7	0.2	26.9	0	0.17
	Wet	70	1.6	16.5	0	18	0.07	0.11
	Dry	9	6.9	2.2	6	3.1	-0.02	0.01
No RF Constraint	Normal	5	4.4	2.8	5.8	1.4	-0.01	0
	Wet	3	1.2	3.6	4	0.7	0	0
	Dry	148	8.9	44.5	1.6	51.8	-0.02	0.09
No Delta Constraint	Normal	68	4.8	19.4	1.9	22.3	-0.08	0.04
	Wet	32	1.2	10.4	1.7	10	0.01	0
	Dry	1692	63.6	302	1.1	364.5		
No Distance Cost	Normal	1893	59.4	348	1.1	406.2		
	Wet	1445	41.4	276.3	1.5	316.2		
	Dry	9929	713	483.5	178.5	1018.1		
No Frictions	Normal	13052	763.3	672.1	170.8	1264.5		
	Wet	14711	787.7	710.4	174.6	1323.5		

Notes: Table reports the levels of various trading outcomes using baseline estimates, and then reports the relative change in those statistics across various counterfactuals. For each counterfactual outcome, I report the average within types of years: Dry, Normal, and Wet. The table reports estimates on years 2012-2015 where 2012 was Wet, 2013 was Normal, and 2014-2015 were dry.