Transaction Costs and the Gains from Trade in Water Markets

Online Appendices

A Institutional Details

A.1 California's water market

Trading is allowed under the Water Code so long as the seller holds legal right to the water and the water would have been used otherwise (DWR and USBR 2019). Transactions may be temporary or permanent; my analysis focuses on within-year leases, the most common form. Many canals have spare capacity, and reservoirs along routes provide storage. Canal owners must grant access for transfers unless negative effects would result (Water Code §1810). Groundwater is regulated separately and cannot be traded over long distances, so it falls outside the scope of my analysis.

Typical sellers are farm-serving districts with secure rights in water-rich areas. Typical buyers include urban districts, agricultural districts in water-scarce areas with higher-value crops, and environmental programs seeking to increase instream flows. Trading helps districts respond to short-term drought shocks and long-term shifts in water demand and urban growth (Hanak and Stryjewski 2012; DWR and SWRCB 2015).

A.2 Water rights and allocation percentages

Many districts directly hold surface water rights, which come in two types: appropriative and riparian. Other districts hold delivery contracts with the federal and state water projects, in which case the project itself holds the underlying water right.

Surface water is scarce and rationed annually, creating year-to-year variation in districts' endowments based on winter precipitation and runoff. Most variation comes from the SWP and CVP. Deliveries from these projects equal a district's time-invariant maximum contract volume multiplied by that year's allocation percentage, which is determined separately for 13 categories of contracts grouped by history, geography, and sector. Some categories tend to have higher priority, but the ordering varies with regional water conditions. Allocation percentages do not fully determine water deliveries, as districts can trade water, take less than their allocation, bank water for temporary storage, or apply for extra water under certain conditions.

Other sources of surface water are more stable. The Lower Colorado system saw no shortages before 2023. Appropriative rights follow a seniority rule: in dry years, senior rights-holders receive their full claim before junior holders receive any. The SWP and CVP are junior to all other rights, so cutbacks mainly affect project contractors (DWR and USBR, 2019).

A.3 Transaction costs

Bretsen and Hill (2009) argue that "transaction costs become a de facto tax on the transfer of water rights," creating a "chilling effect" that deters trades. A few studies provide empirical evidence that transaction costs impede trade (Archibald and Renwick, 1998; Carey et al., 2002; Regnacq et al., 2016), though they focus on quantities traded rather than monetizing the costs or forgone gains.

Internal decision costs. Anecdotal evidence suggests intra-district costs are substantial. Libecap (2011) notes that in the 1990s and 2000s, the Palo Verde Irrigation District, controlled by landowners, transferred water to the Los Angeles area "with little controversy," while the neighboring Imperial Irrigation District, elected by popular vote, considered the same but was "mired in lengthy, complex negotiations."

These costs are shaped by governance structure. Some boards are elected by popular vote, others by property-weighted vote. Generally, irrigation districts use popular voting; water and water storage districts use landowner voting weighted by assessed value; reclamation districts by land area; and mutual water companies by shareholder holdings. But districts in California are authorized under more than 140 statutes so there are exceptions (Thompson, Barton H., Jr., 1993). Districts controlled by landowners tend to be more willing to sell water than those that respond to the broader community, as sales often benefit landowners while harming others. Decision costs are likely higher for districts that answer to more, and more heterogeneous, constituents than for those run by a small group of farmers growing similar crops (Hanak, 2003; Bretsen and Hill, 2009; Edwards and Libecap, 2015; Bruno et al., 2024).

Administrative costs. First, potential buyers and sellers must identify trading opportunities, find a willing trading partner, and learn about their preferences. Matches are usually made through word of mouth but sometimes with help from a professional broker. Second, the districts must negotiate price, quantity, timing, delivery point and route, payment terms, and responsibility for related costs (SWRCB, 1999). Third, they must draft, execute, and later enforce a contract. Archibald and Renwick (1998) call these administratively-induced costs.

Regulatory costs. Transfers require documentation of compliance with state and federal environmental and endangered species laws. Reviews focus on identifying "new" or "wet" water – the consumptive use that would have occurred absent the transfer (Hanak and Stryjewski, 2012). The seller files a petition following guidelines in SWRCB (1999) or DWR and USBR (2019). Because California lacks standardized diversion metering, transfers must be based on verifiable forbearance actions. For example, for a transfer based on crop idling, sellers must submit 5–20 years of crop history, detailed maps, and a hydrological water budget. Once filed, the petition enters public review. Other parties can protest, requiring the seller to respond. If conflicts are not resolved through negotiation, the agency holds a public hearing. Agencies encourage pre-filing consultations with all relevant agencies, environmental groups, and other water users to prevent conflicts. After approval, monitoring is strict and can include field inspections and even soil sensors (DWR and USBR, 2019).

Agencies charge a petition fee plus full reimbursement for review and administration. Sequential agency reviews can take so long that the transfer is no longer needed (Sellers et al., 2016). Third-party protests add risks, delays, and costs of negotiation, mitigation, and compensation. A large Imperial–San Diego transfer included a $20 million mitigation fund (Hanak, 2003). A 2012 transfer between Modesto Irrigation District and San Francisco's utility was abandoned due to local opposition (Regnacq et al., 2016).

Delivery costs. Wheeling charges have been called "barrier pricing" (Western Water Company, 2000). They can be so high as to effectively double the price of water, such as in 1998 when

Metropolitan charged $262 per acre-foot to transport water between Imperial and San Diego (Chong and Sunding, 2006).

Carriage losses involve water that is sent to sea to maintain outflows and prevent ocean salinity from harming ecosystems and other water rights (DWR and USBR, 2019).

Restrictions on DWR and USBR pumping through the Delta protect water quality and species under the Endangered Species Act. They are governed by a 2008 biological opinion from the U.S. Fish and Wildlife Service covering Delta smelt and a 2009 biological opinion from the National Marine Fisheries Service covering anadromous fish (such as Chinook salmon) and marine mammals (DWR and USBR, 2019). One cost is greater effective losses: transfers are limited to specific months, and if sellers cannot store water received outside this window, only part of the water they forgo using can actually be transferred. A separate cost is delivery risk; Johnson (2015) reports that Metropolitan lost two-thirds of a $13 million water purchase in 2003.

A.4 Persistence of transaction costs

Why do transaction costs persist if there are gains to eliminating them? The literature offers two main explanations. First, some transaction costs are efficient. Many delivery costs are the unavoidable result of physics. Regulatory reviews clarify and protect property rights (Libecap, 2009) and reduce the harms of transfers by internalizing external costs (Colby, 1990; Culp et al., 2014). Still, overregulation is possible (Colby, 1990), and reviews introduce asymmetry: transfers face greater scrutiny than initial rights, and reviews seek to prevent all harm rather than weigh benefits against costs. Second, historical path dependence and distributional conflict impede reform. California's water institutions were built to move water into agriculture and are poorly suited to the reverse (Bretsen and Hill, 2009). Institutional change is costly, creates winners and losers, and generates uncertainty (Demsetz, 1967; Edwards and Libecap, 2015). Selling water often concentrates benefits among a subset of farmers while imposing costs on other farmers and community members (Leonard et al., 2019).

B Estimation of the Inverse Price Elasticity of Demand

B.1 Instrument construction

My instruments are log allocation percentages for the district itself, all other districts in the same hydrologic region, and all other districts in the state, and the full set of interactions between each contract type's log allocation percentage and hydrologic region indicator variables. These interactions allow allocations for each contract type (which are largely divided by region and sector) to have different effects on every other region of the state. They also yield a large number of candidate instruments: There are 13 contract types and 10 hydrologic regions, plus 3 overall instruments, for a total of 133 potential instruments. All instruments are log-transformed to match the variation of the endogenous variable, log quantities. Using all the instruments would risk overfitting and weak instrument bias, so instead I estimate the model via post-lasso two-stage least squares, as implemented in Stata by Ahrens et al. (2018).

B.2 Identification assumptions

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

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

The exclusion restriction is also plausible in this setting. Allocation percentages are pure supply shocks. Increasing one district's surface water allocation will increase quantities and decrease equilibrium prices, moving along demand curves without changing underlying preferences. Increasing other districts' allocations will lower their marginal valuations, raising quantities traded, decreasing equilibrium prices and again increasing the first district's quantity. Substitution to groundwater or storage does not violate the exclusion restriction, which simply requires that any allocations-driven changes in quantities also be reflected in prices.[41]

B.3 Comparisons with prior literature

I estimate a price elasticity of demand for water districts, whereas previous estimates of price elasticities are for retail customers. For municipal water demand, my estimate is larger than Buck et al. (2016) in California (−0.14) and the US mean in Dalhuisen et al. (2003) (−0.41) but similar to Baerenklau et al. (2014) in Riverside County (−0.76). For agriculture, my estimate exceeds groundwater elasticities for California (Bruno and Sexton 2020, −0.19) and Kansas (Hendricks and Peterson 2012, −0.10), and the US mean in Scheierling et al. (2006) (−0.48). In these studies, even when quantity data is at the district level, the price under question is the retail price.

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

C Simulation Details & Further Results

C.1 Simulation details

Sample. For the simulation, I select districts whose mean quantity consumed is greater than 25,000 acre-feet per year. 154 districts remain, which together consume 85% of the water in California. Because surplus is roughly proportional to the square of trading quantity, these districts are likely responsible for more than 85% of the potential gains from trade.

Most of these districts contribute to demand estimation: 53% appear in the transactions data, or 72% when weighted by water use. Districts that appear in transactions data do so in 30% of years on average. In an average year, 12% of all simulation districts appear in the transactions data. Appendix Figure A3(b) plots market participation rates by year. Appendix Table A4 shows that districts never observed trading are smaller (fewer water rights) and less likely to be in the CVP, but broadly similar in other ways.

Demand extrapolation. To extrapolate the demand model to districts never observed trading, I project the estimated district-specific intercepts $\hat{\bar{v}}_j$ onto the district covariates from Step 4. (Covariates also include hydrologic region indicators, and regression results are shown in Appendix Table A5.) This step replaces the unrestricted heterogeneity in $\bar{v}_j$ with a parametric model based on observable district characteristics. I then generate fitted values and use them as the demand intercepts in simulations for all districts (including those observed trading, for consistency).

Water-supply scenarios. These scenarios draw observed quantities and trading volumes from the years 2006, 2010, and 2014, respectively. Summing water quantities across the state over the 1998-2015 period, 2006 is the wettest year in my data, 2014 the least, and 2010 is the median year.

C.2 Further results

Environmental and infrastructure constraints. I also consider capacity constraints at the Colorado River Aqueduct, the only link between the southeastern corner of California and the rest of the state. This aqueduct operates near capacity in some years, so large quantities of new sales from Colorado River districts to urban Southern California may not be feasible. To exclude this possibility, Scenario 6 simulates three separate markets, splitting the south-of-Delta market into two at the Colorado River Aqueduct. Again trading volumes and gains are very similar.

Among only observed traders. How much of the gains from trade rely on extrapolating the demand model out of sample? Scenario 7 simulates trade among only the 82 districts observed in the transactions data. Most gains are still achieved: 63 to 83% of those in Scenario 2. This is because most gains from trade come from large districts, which are more often observed to trade.

Using estimated demand intercepts instead of fitted values. How sensitive are results to applying the extrapolation model universally, rather than only to districts lacking estimates? Appendix Table A6 repeats all simulations using demand intercepts taken directly from the estimated demand model for prior traders. Districts not observed in the transactions data still use fitted values from the extrapolation model. Gains are somewhat larger in most scenarios – for example, 23 to 118% greater in the base scenario – but still within the same order of magnitude. Relative patterns are similar across scenarios.

Functional form. How sensitive are results to the functional form of demand? Scenario 8 optimizes trade and evaluates gains using linear demand instead of isoelastic. Gains are lower – 64 to 76% of Scenario 2 – but otherwise broadly similar. This suggests that the qualitative implications of my results are not driven by the choice of functional form.

D Tables and Figures

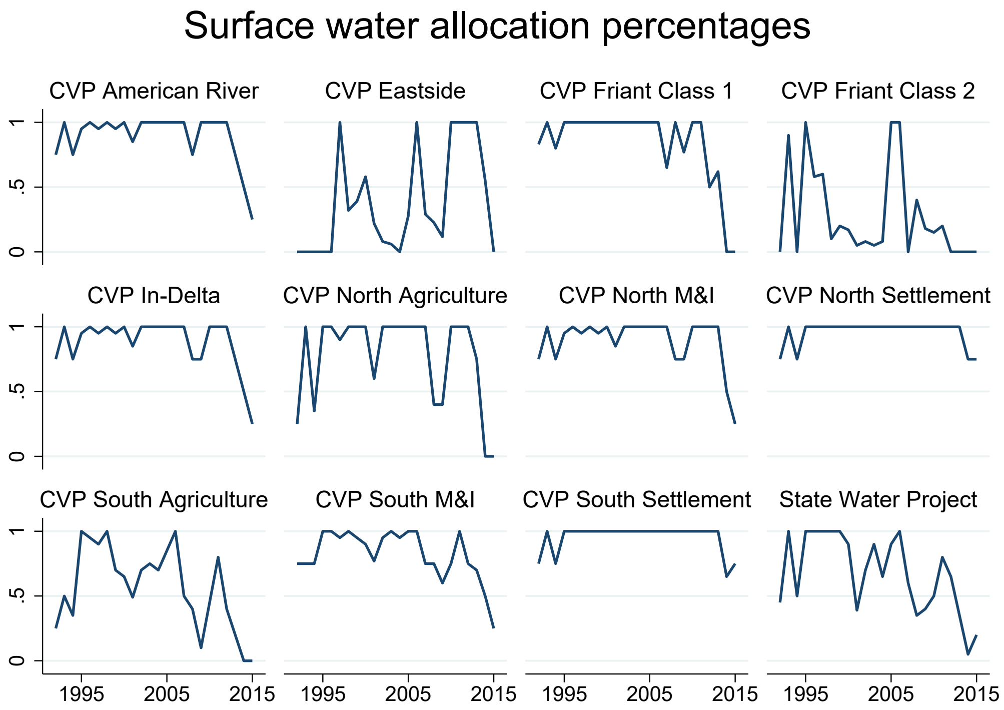
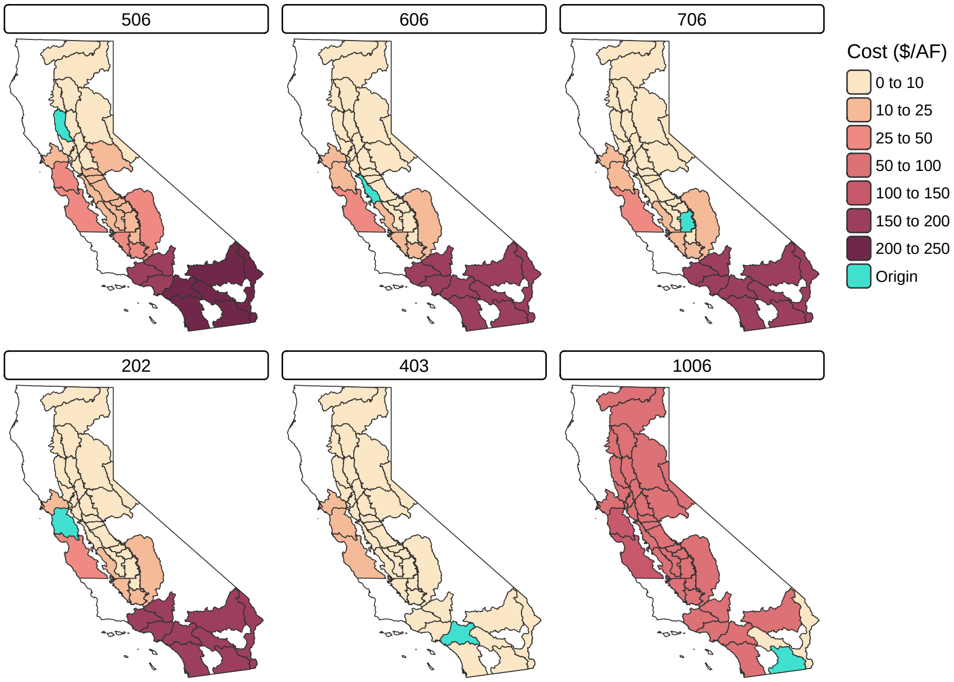
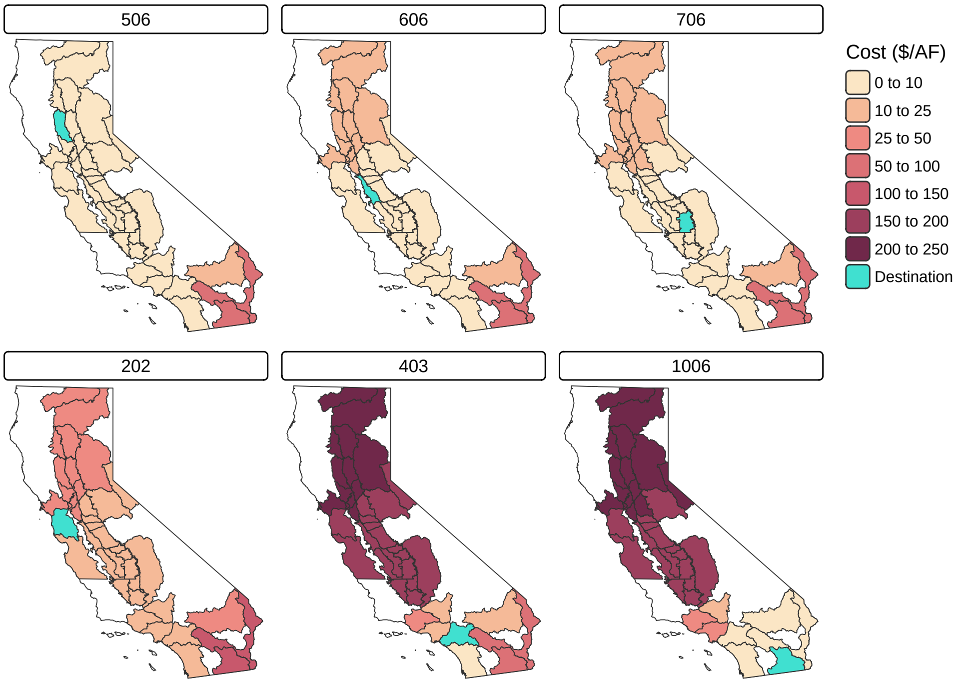


Figure A1: Variation over time in allocation percentages for each category of contracts with the federal and state water projects (CVP = Central Valley Project, M&I = Municipal & Industrial). These allocation percentages are used as instruments to estimate demand elasticities. This figure combines agricultural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



(a) Modeled conveyance costs from selected origins



(b) Modeled conveyance costs to selected destinations

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

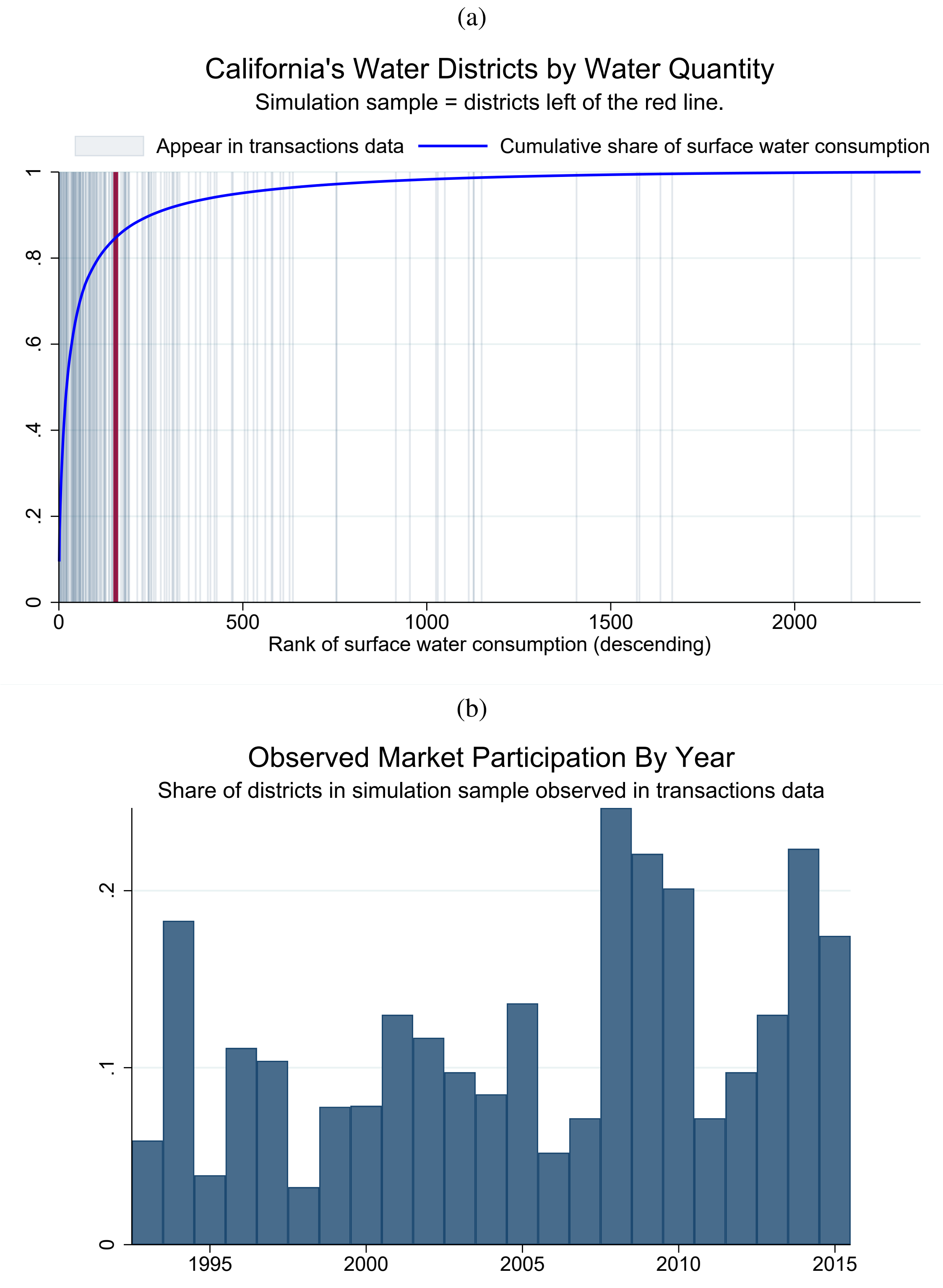


Figure A3: Districts in the simulation sample, by surface water quantity consumed and appearance in the transactions data. Panel (a) plots the cumulative density of surface water use in the state for the full analysis sample (i.e., all water districts in California that consume at least 100 acre-feet per year). The background is shaded for districts that also appear in the transactions data. The simulation sample lies to the left of the vertical red line (i.e., the 154 districts with more than 25,000 acre-feet/year). Panel (b) plots the share of districts in the simulation sample that appear in the transactions data in each year.

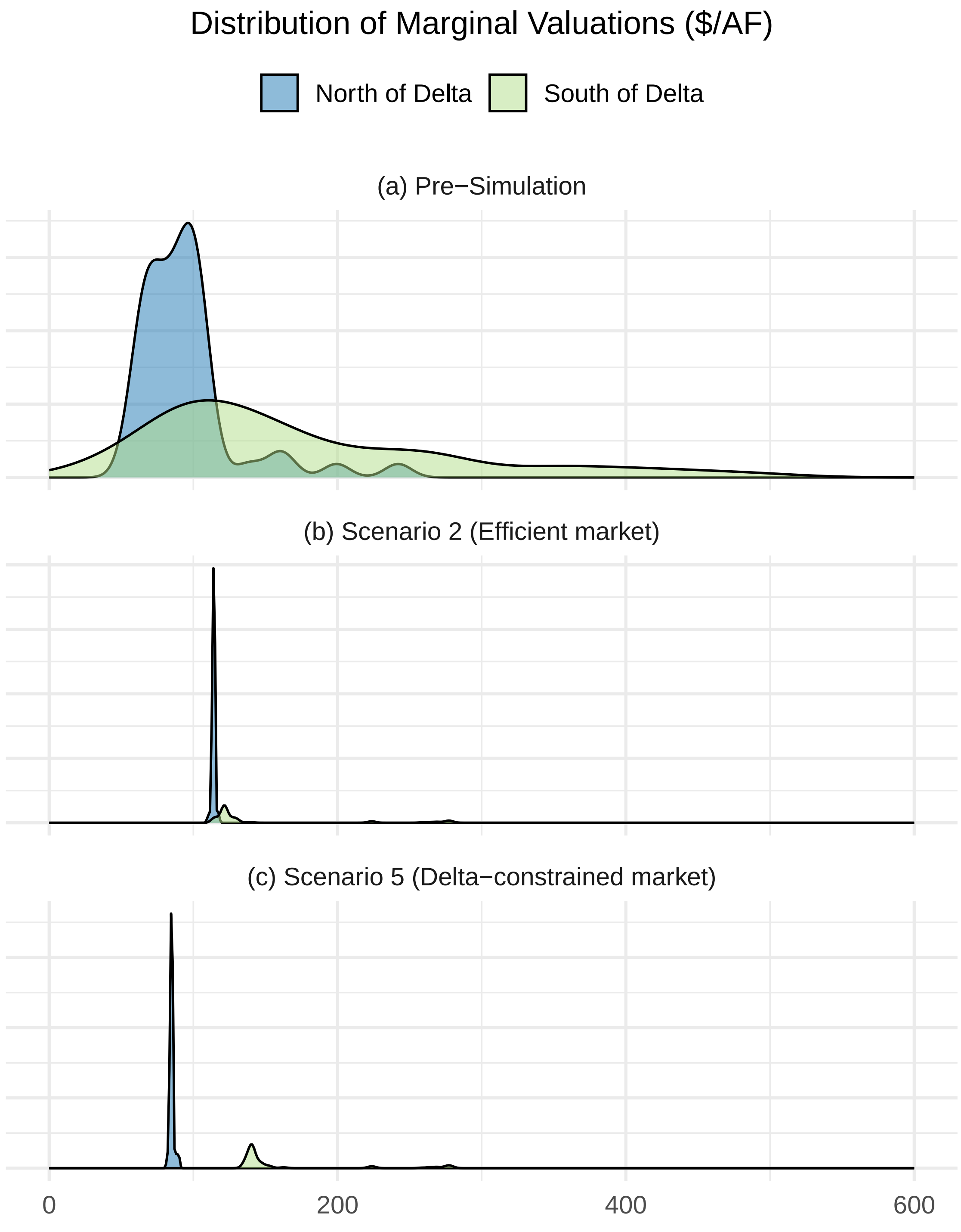


Figure A4: Kernel density estimates of marginal valuations for median-year scenarios. Panel (a) plots estimated marginal valuations before simulations. Panels (b) and (c) plot final marginal valuations after simulations in Scenarios 2 and 5 – with and without the environmental constraint at the Delta. Observations are water districts.

Table A1: Variable Transaction Costs from Observed Determinants: Robustness Checks

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

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

Table A2: Inverse Price Elasticity of Demand: Robustness Checks

	Adjusted log price				Unadjusted	Adjusted
	(1)	(2)	(3)	(4)	(5)	(6)
Log quantity consumed	–1.9***	–1.7***	–1.4**	–1.5**	–1.5**	–0.91*
	(0.48)	(0.46)	(0.62)	(0.46)	(0.48)	(0.52)
Inverse Mills ratio	–0.22*	–0.085	–0.10		–0.069	–0.17
	(0.072)	(0.075)	(0.069)		(0.065)	(0.066)
District fixed effects	✓	✓	✓	✓	✓	✓
Linear time trend		✓	✓	✓	✓	✓
Planning area X time trend	✓					
Year fixed effects						✓
Candidate instruments	All	Overall	Regional	All	All	All
Lasso-selected instruments	3	2	4	3	3	3
Observations	972	972	976	981	978	972
Clusters	155	155	156	155	156	155
First-stage F-statistic	53	49	39	47	50	12
Sup-score weak-ID test	reject	reject	reject	reject	reject	fail to reject

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

Table A3: District Intercepts of Marginal Valuations (Step 4)

	Adjusted Log Price
Serves primarily municipal customers (=1)	0.17
	(0.12)
Central Valley Project contractor (=1)	–0.096
	(0.11)
State Water Project contractor (=1)	0.53***
	(0.15)
Lower Colorado rights holder (=1)	0.73**
	(0.17)
Surface water rights holder (=1)	0.51***
	(0.096)
Log maximum water rights (centered)	–0.14***
	(0.039)
Latitude (degrees, centered)	–0.12*
	(0.061)
Constant	4.8***
	(0.14)
Var(District indicators)	0.55
	(0.24)
Var(District/counterparty pair)	0.35
	(0.067)
Var(Residual)	0.27
	(0.068)
Observations	965
Clusters	154

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

Table A4: Summary statistics for water districts used in simulations

Panel A: Districts observed in transactions data

Variable	Mean	SD	Obs.
Serves primarily municipal customers (=1)	0.12	0.33	82
Central Valley Project contractor (=1)	0.59	0.5	82
State Water Project contractor (=1)	0.18	0.39	82
Lower Colorado rights holder (=1)	0.061	0.24	82
Surface water rights holder (=1)	0.65	0.48	82
Maximum water rights (TAF/year)	283.2	515.2	82
Latitude (degrees)	37.1	1.8	82
Marginal valuation of water, estimated mean (2010$/AF)	144.7	95.2	82

Panel B: Districts not observed in transactions data

Variable	Mean	SD	Obs.
Serves primarily municipal customers (=1)	0.17	0.38	72
Central Valley Project contractor (=1)	0.11	0.32	72
State Water Project contractor (=1)	0.12	0.33	72
Lower Colorado rights holder (=1)	0.014	0.12	72
Surface water rights holder (=1)	0.86	0.35	72
Maximum water rights (TAF/year)	107.1	137.1	72
Latitude (degrees)	37.2	2.0	72
Marginal valuation of water, estimated mean (2010$/AF)	155.9	82.9	72

Summary statistics for the set of water districts selected for simulations (i.e., all water districts that consume more than 25,000 AF/year), tabulated separately by whether districts are ever observed in the transactions dataset. Districts in Panel A are observed in the transactions data and therefore contribute to model estimation. Districts in Panel B are not, so their demand parameters are extrapolated from the estimated model on the basis of district covariates. TAF = thousand acre-feet.

Table A5: Extrapolation Model of District-Specific Demand Intercepts

	Estimated Mean Marginal Valuation
Serves primarily municipal customers (=1)	0.11
	(0.44)
Central Valley Project contractor (=1)	–0.26**
	(0.12)
State Water Project contractor (=1)	0.51**
	(0.26)
Lower Colorado rights holder (=1)	0.36
	(0.42)
Surface water rights holder (=1)	–0.20
	(0.17)
Log maximum water rights (centered)	–0.079
	(0.049)
Latitude (degrees, centered)	–0.083
	(0.12)
Hydrologic region: San Francisco Bay (=1)	0.85
	(0.68)
Hydrologic region: Central Coast (=1)	0.041
	(0.78)
Hydrologic region: South Coast (=1)	0.51
	(0.94)
Hydrologic region: Sacramento River (=1)	0.17
	(0.77)
Hydrologic region: San Joaquin River (=1)	0.13
	(0.81)
Hydrologic region: Tulare Lake (=1)	0.38
	(0.86)
Hydrologic region: South Lahontan (=1)	0.40
	(0.82)
Hydrologic region: Colorado River (=1)	0.011
	(0.86)
Constant	5.0***
	(0.75)
Observations	1,061
Clusters	154
R-squared	0.45

Regression of district-specific demand intercepts, as estimated in Step 4, on district-level variables. Observations are transactions made by each water district. Robust standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A6: Annual Economic Gains from Surface Water Markets: Robustness Checks

Using Estimated Demand Intercepts for Observed Traders

Conditions	Additional volume traded (TAF)	Average equilibrium price ($/AF)	Avoided costs of observed transactions (millions)	Gains from new transactions (millions)
Scenario 2: Efficient market (with only physical costs of conveyance)				
Dry	4,497	$ 201	$ 105.2	$ 685.2
Median	4,323	$ 154	$ 37.9	$ 460.1
Wet	4,271	$ 140	$ 5.7	$ 382.2
Scenario 3: With fixed transaction costs				
Dry	1,798	$ 250	$ 70.8	$ 437.7
Median	1,331	$ 175	$ 33.4	$ 93.2
Wet	908	$ 146	$ 2.5	$ 92.4
Scenario 4: No conveyance costs				
Dry	5,341	$ 231	$ 116.1	$ 1,333.3
Median	5,898	$ 189	$ 77.2	$ 988.0
Wet	6,197	$ 171	$ 13.4	$ 1,005.7
Scenario 5: With a key environmental constraint (Sacramento River outflow held fixed)				
Dry	3,953	$ 204	$ 85.9	$ 632.9
Median	3,986	$ 154	$ 35.9	$ 448.7
Wet	4,089	$ 140	$ 5.3	$ 373.0
Scenario 6: With more capacity constraints (Sac. River and Colorado River Aqueduct held fixed)				
Dry	3,953	$ 204	$ 85.9	$ 632.9
Median	3,991	$ 153	$ 39.2	$ 445.7
Wet	4,066	$ 139	$ 5.3	$ 371.7
Scenario 7: Among only prior traders (districts observed in the transactions data)				
Dry	3,248	$ 230	$ 94.3	$ 519.4
Median	3,393	$ 167	$ 41.3	$ 374.2
Wet	3,463	$ 137	$ 5.5	$ 382.8
Scenario 8: Linear demand (instead of isoelastic)				
Dry	3,520	$ 135	$ 103.0	$ 435.2
Median	4,026	$ 110	$ 38.7	$ 325.1
Wet	3,996	$ 103	$ 3.4	$ 299.0

Per-year welfare analysis of counterfactual simulations in which demand intercepts are taken directly from the estimated demand model for districts observed in the transactions data. Districts not observed trading still use fitted values from an extrapolation model. Each scenario is run under dry, median, and wet conditions, which draw quantities and trading volumes from the years 2014, 2010, and 2006, respectively. All dollar figures are in 2010 USD; gains are per year. TAF = thousand acre-feet.

E Theory and Proofs

E.1 Motivating no-arbitrage

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

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

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

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

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

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

E.2 Year effects bias elasticity estimates when comparing within a common market

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

E.3 Solution to the planner's problem has the same necessary conditions as the market equilibrium

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

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

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

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

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

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

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

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

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

E.4 Sum of district-specific gains equals the maximand

District-specific gains are defined as:

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

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

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

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

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

which is the second term of Equation 14.

F Data Processing

F.1 Water Transactions Data

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

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

Sample restrictions. To focus on transactions of actual surface water, I drop transactions of rights to pump groundwater within adjudicated basins, rights to store water in reservoirs or groundwater banks, and desalinated water. To focus on transactions in which the price is freely negotiated, I drop transactions within programs in which prices are set administratively. I drop one transaction that never cleared. Transactions that remain are those of surface water originating in appropriative or riparian rights, SWP or CVP contracts, or reservoir storage, in which the price is freely negotiated. Price is observed for 95% of these transactions; I drop the 57 transactions that lack a price, leaving 2,584 transaction-by-party observations from 1,104 unique transactions. Finally, I restrict the main analysis to the spot market (i.e., within-year leases) by dropping transactions longer than one year. I carry forward 1,628 transaction-by-party observations from 705 unique spot-market transactions.

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

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

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

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

3. Keywords (9%). I classify users based on the following keywords in their name. Agriculture: almonds, citrus, contractors, dairies, dairy, famers, farm, farmers, farming, grower,

irrigating, irrigation, nurseries, nursery, orchard, ranch, trust. Municipal: cement, cemetery, chemical, Chevron, church, city of, college, communities, community services, companies, company, corporations, developer, development, electric, energy, estate, gardens, golf, gravel, homeowners, homes, housing, inc., Indians, industries, investment, landscaper, leasing, LLC, LP, military, municipal, mutual water, non-ag, oil, owners, park, paving, power authority, properties, property, railway, real estate, realty, recycled, refining, replenishment district, retail, sanitation, school, Texaco, town of, tribe, university, ventures. Environmental: conservancy, duck hunting, ducks, fish & wildlife, forest service, forestry & fire prevention, water bank.

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

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

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

F.2 Merged Dataset

For analysis, I construct a balanced panel of surface water quantity consumed for all 2,380 districts in California that consume at least 100 acre-feet per year, as measured by maximum water rights or average quantity consumed, whichever is greater. Water rights smaller than 100 AF/year constitute 67 percent of the count of observations but only 0.2 percent of total water consumption; they are generally held by individual farmers and rural households not served by any water or irrigation district.

To this dataset, I merge transactions observed for each district. I keep transactions even when they do not successfully match the water quantity data, allowing me to use all available data at each step of the estimation: Steps 1-2 use data from 1990-2015, including districts without quantity data, while steps 3-4 use data from 1993-2015 for districts with quantity data. Unmatched districts represent 14% of the transaction-district observations and generally fall into two categories: associations that occasionally trade on behalf of multiple districts, and small districts that hold affiliations or agreements with larger districts instead of their own water rights or contracts. I drop a small number of districts not identified with enough specificity to determine the transaction cost variables. I also drop those that purchase water for instream flows and other environmental purposes, rather than for consumptive use in the agricultural and municipal sectors.

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