NBER WORKING PAPER SERIES

HOW TRANSACTION COSTS OBSTRUCT COLLECTIVE ACTION: EVIDENCE FROM CALIFORNIA'S GROUNDWATER

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Working Paper 23382
http://www.nber.org/papers/w23382

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
May 2017

We acknowledge excellent research assistance provided by Jennifer Laws as well as helpful comments from Zeynep Hansen, Gabe Sampson, Sherzod Akhundjanov, Ryan Abman and participants at the 2016 IWREC Annual Meetings, the 2016 Southern Economics Association Meetings, and the 2016 Western Economic Association International Annual Meetings. This research was funded by a grant through the UC Office of the President: MR-15-328650, Legal and Economic Data and Analysis of Environmental Markets and through UAES Project UTA01197. The views expressed herein are those of the authors and do not necessarily reflect the views of the National Bureau of Economic Research.

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NBER Working Paper No. 23382
May 2017
JEL No. K11,N52,P48,Q15,Q25,Q58

ABSTRACT

Collective action to remedy the losses of open access to common-pool resources often is late and incomplete, extending rent dissipation. Examples include persistent over-exploitation of oil fields and ocean fisheries, despite general agreement that production constraints are needed. Transaction costs encountered in assigning property rights are an explanation, but analysis of their role is limited by a lack of systematic data. We examine governance institutions in California's 445 groundwater basins using a new dataset to identify factors that influence the adoption of extraction controls. In 309 basins, institutions allow unconstrained pumping, while an additional 105 basins have weak management plans. Twenty of these basins are severely overdrafted. Meanwhile, users in 31 basins have defined groundwater property rights, the most complete solution. We document the critical role of transaction costs in explaining this variation in responses. This research adds to the literatures on open access, transaction costs, bargaining, and property rights

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I. Introduction

Common-pool resources are subject to excessive exploitation and rent dissipation due to the absence of economic property rights (Gordon, 1954; Coase, 1960; Hardin, 1968; Cheung, 1970; Ostrom, 1990). Remedies often are implemented late and are incomplete. Distributional conflicts among actors over property rights and the corresponding allocation of benefits and costs raise transaction costs, impeding more timely and complete collective action. We define transaction costs as the costs of defining and enforcing property rights (Allen, 1991, 2000).

Wiggins and Libecap (1985) find that agreement on oil field unitization to avoid competitive drilling and extraction is constrained by the number and heterogeneity of firms. Libecap and Smith (1999, 545) argue that output on the giant Prudhoe Bay field in Alaska went into premature decline in 1988, not because of waning deposits, but because of a failure of the parties to implement complete unitization. Wild-ocean Atlantic Bluefin Tuna, perhaps the world's most valuable fish, has long been overharvested, depleting stocks, but relevant fishing countries have been unable to agree upon a sustainable total annual allowable harvest and the distribution of catch shares within it (Bjørndal and Brasão 2006, 193-7; Ellis 2008; Webster, 2010, 328; Korman 2011, 701-3, 740). Finally, water is critical for life and also as an input into production, but groundwater commonly is exploited under open access with excessive pumping and depletion worldwide, despite evidence of serious losses (Konikow and Kendy, 2005; Zekri, 2008; Giordano, 2009; Barlow and Reichard, 2010; Aeschbach-Hertig and Gleeson, 2012).

There have been few opportunities to empirically examine how transaction costs arise and affect collective responses to such common-pool problems. Using a novel, newly assembled dataset, we examine varying governance institutions across California's 445 groundwater basins to identify factors that influence the adoption of extraction controls: The default institutional regime, retained in 309 basins, allows unconstrained pumping by surface property owners, and in 105 basins users have adopted weak groundwater management plans. Twenty of these basins with limited or no controls are severely overdrafted. Meanwhile, users in 31 basins have defined groundwater property rights through costly court adjudication, which is the most complete solution. We exploit this variation in analyzing the factors affecting when any controls will be implemented and when property rights will be assigned. We find that agents are more likely to agree on pumping limits where aggregate benefits exceed transaction and implementation costs. Benefits rise as the resource becomes more common, as cross-well impacts become more severe, and as groundwater values rise. Costs rise with basin size and the number and heterogeneity of users.

Our analysis proceeds with an ordered-logit model to uncover the determinants of aggregate benefits. We then examine the impact of transaction costs on the variation in management arrangements by comparing the characteristics of adjudicated and critically overdrafted basins, which serve as counterfactuals for one another. We also investigate the determinants of how long it takes to agree to a property rights distribution and the sources of fragmentation of groundwater management plans that would otherwise be more effective as a single unit.

II. Background

A. Bargaining over Property Rights to a Common Pool

Institutional remedies mitigate common-pool losses. In Kansas, for example, groundwater management districts were implemented in the early 1970s to control well spacing and pumping in order to address growing local depletion (Edwards, 2016). In Nebraska, groundwater rights and markets were developed to reduce pumping in areas where declining groundwater levels reduced surface water flows (Kuwayama and Brozovic, 2013). Collective action to adopt such arrangements requires agreement by users on resource access and extraction rules, monitoring, and enforcement. An efficient response to the losses of open access occurs when aggregate benefits exceed costs (Demsetz, 1967), but even where there appear to be positive net gains, agreement may not be forthcoming (Leonard and Libecap, 2015). Some users who do well under the *status quo* may rationally oppose the transition from unconstrained exploitation (Grainger and Costello, 2015; Sutherland, 2016), and the costs to bring them on board may be very high (Johnson and Libecap, 1982; Wiggins and Libecap, 1985).

Conflicting positions arise when users perceive different private net returns from mitigation. When the resource stock is large, migratory, and heterogeneous, information about and perception of rent dissipation varies, leading to different assessments about the need for corrective action. Additionally, when there are large numbers of agents who differ in asset values, production costs, exploitation rates, and open-access losses, there are varied incentives to support constraints (Adhikari and Lovett, 2006; Ruttan, 2008). Under these circumstances, monitoring and enforcement costs for any adopted arrangement rise, lowering expected net returns from any agreed-upon remedy.

B. Groundwater as a Common-pool Resource

Groundwater users share a finite, often renewable, amount of water that migrates across an aquifer according to subsurface conductivity. Each pumper's use can reduce the water available to neighboring wells and raise pumping costs. Each well creates a cone of depression, or local drawdown, within a radius around it, encouraging water migration from elsewhere in the formation (Brederhoeft et al., 1982; Brozovic et al., 2010; Guilfoos et al., 2013; Edwards, 2016).[4] These cross-well effects depend upon well proximity and hydraulic conductivity, the measure of the degree to which the aquifer is held in common. Cross-well interference rises with greater well density, higher conductivity, and more rapid pumping rates. In addition, excessive pumping can compact subsurface formations, a process known as subsidence, which permanently reduces storage capacities and disrupts surface landscapes and the roads, structures, and farmland upon them. Finally, where basins border the ocean, as the water level falls, seawater enters the formation, rendering groundwater unfit for agricultural uses and increasing treatment costs for drinking water (Zekri, 2008; Barlow and Reichard, 2010).

Because pumpers recognize these externalities, they have an incentive to more rapidly drill and drain the basin than would be optimal with a sole owner (Brozovic et al., 2010; Koundouri, 2004).[5] Capital investment increases, storage of future water supplies is foregone, water tables decline, and pumping costs rise (Famiglietti et al., 2011; Scanlon et al., 2012; Farr et al., 2015). As rents are dissipated, pumpers in aggregate are better off with pumping restrictions, but no user faces a unilateral incentive to reduce extraction, so collective action is required to implement group restraints. Users become more aware of these losses as water tables drop, raising perceived benefits of implementing controls (Nachbaur, 2014). In areas of low precipitation, surface water is limited and aquifer recharge is low, increasing the value of groundwater and the returns from conserving it (Edwards, 2016). Higher expected water values and associated benefits from storage and reallocation across time also encourage controls (Brill and Burness, 1994). Higher conductivity and exposure to collateral impacts do the same.

[4] This is true of an unconfined aquifer. In a confined aquifer, pumping creates a cone of depression in the potentiometric surface, the pressure at which the water is confined. The effect on other wells is similar.
[5] In large, homogeneous groundwater basins with spaced pumpers, externality costs can be small with open access the first-best outcome (Gisser and Sanchez, 1980).

C. *Options for Groundwater Management in California*

Historically, groundwater extraction in California has been molded by the correlative rights doctrine, whereby all landowners overlying an aquifer pump water relatively unconstrained. Other parties, such as water utilities, hold subordinate appropriative water rights that allow them to pump and transport water for use elsewhere. Although the current institutional framework restricts the number of pumpers to those who hold either correlative or appropriative rights, it does not effectively cap the number of wells drilled or aggregate pumping rates.

Options for greater control include, in order of restriction: (1) groundwater property rights implemented via court order through adjudication; (2) the formulation of groundwater management plans that generally do not constrain pumping, but may assign spacing rules to limit cross-well externalities; and (3) the *de facto* system of correlative and appropriative water rights that allows for additional wells and competitive extraction.

Adjudication

Adjudication is the most complete remedy for over-extraction because groundwater property rights are assigned to well owners. In the adjudication process, agents come before a state court to request a cap on all extraction that is consistent with the annual safe yield of the basin.[6] Safe yield is estimated and distributed among existing pumpers, usually as a share based on historical extraction, thereby grandfathering overlying and appropriative users. A third-party water master is identified by the court to enforce the new system of economic property rights. Groundwater rights can be transferable, allowing for gains from trade as well as the voluntary consolidation and closing of wells. Because agents may disagree on their shares of the new total allowable extraction, adjudication can be costly and take considerable time. Despite legal

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[6] Safe yield typically refers to a rate of aggregate pumping that should maintain existing water table elevations in the long term.

precedents for adjudication starting in the 1940s and 1950s, only 25 adjudications have been completed, covering 31 groundwater basins out of the 445 in California.[7]

Groundwater Management Plans

A lower-cost and less-complete option is a groundwater management plan (GMP). GMPs do not define groundwater rights nor generally restrict individual well pumping. Rather, they monitor the number of active and abandoned wells, may establish well spacing requirements, install infrastructure to limit seawater intrusion and to import surface water to offset overdraft, and remediate pollution. Authorized since the early 1990s, GMPs are voted on by a majority of basin landowners, often with little opposition (McGlothlin, 2016). If a basin-wide GMP does not receive majority support, then it must be abandoned, at least for a year. Although a single GMP would most effectively address basin-wide externalities, in many cases, users have chosen to adopt multiple, more narrow partial-basin plans.

De facto Open Access

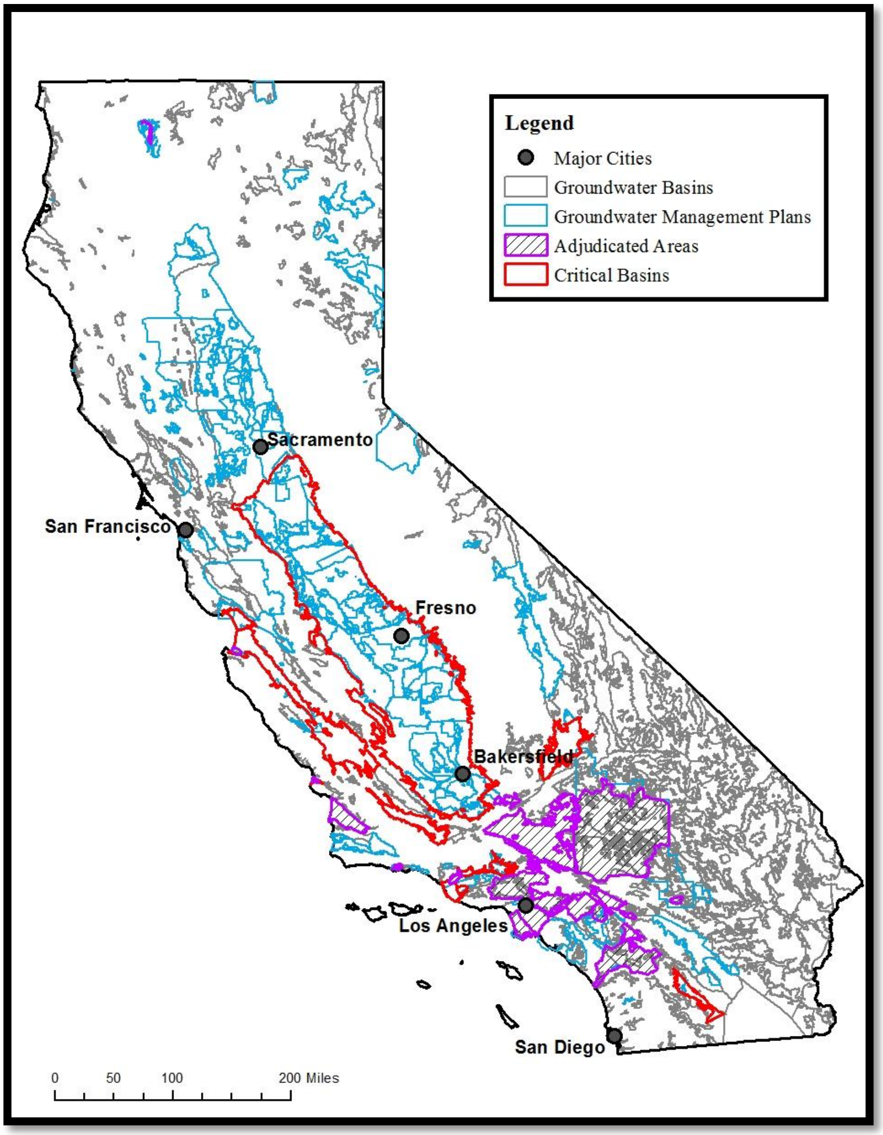
Absent adjudication or a GMP, correlative and appropriative water rights holders generally extract water without constraint, adding wells and adjusting pumping rates as individually desired.

Accordingly, there is considerable variation in the response to potential open access losses in groundwater; we examine the factors that underlie that variation. Figure 1 shows governance regimes for the 445 groundwater basins in the state. The 309 grey-lined basins are not formally managed, and are found largely in remote areas. The 131 blue-lined polygons identify groundwater management plan areas. One hundred and five of these have multiple

[7] The first adjudications were the Raymond Basin and the Upper Los Angeles River Basin. Adjudication can be initiated either by lawsuit or by cooperative negotiations among users. DWR identifies 430 groundwater basins, but when the largest, San Joaquin, is divided into subbasins, the number is 445, which we use here.

GMPs, covering different parts of a basin, such as the 63 GMPs above the San Joaquin Valley basin. The 25 purple-lined and cross-hatched polygons designate adjudicated areas, covering 31 groundwater basins. These are primarily in more arid, urban southern California. Finally, the 20 red-lined basins are designated as critically overdrafted. Of these, some have no governance regimes, while most have limited GMPs. These GMPs have not prevented critical overdraft.[8]

Figure 1: Locations of California's Groundwater Management Institutions



[8] Of the 20 critically overdrafted basins, 2 have adjudicated portions: the Salinas Basin (Seaside, 2006) and the Santa Clara Valley Basin (Santa Paula, 1996). In addition, the Los Osos Valley Basin (2015) was adjudicated too recently to determine the resulting changes in overdraft.

III. Analytic Model

We model the behavior of groundwater users, primarily agriculture and utilities providing water service to municipalities. We assume that the goal of each is to maximize profits, defined as the benefits of water use, minus the costs of pumping. Heterogeneity across user benefits and costs affect transaction costs and the type and timing of governance adopted.

Consider the decision problems faced by any groundwater user. The pumper must choose how many wells to drill, where to site them, and the rate of pumping. The number of wells and place are constrained by the physics of pumping and the cost of building a new well. For a sole-owner of land above an aquifer, a new well is typically drilled to access water at a different location. Pumping effects are additive, so two small wells are constrained in the same manner as a single, large well. We assume that wells are placed by a sole-owner when the benefits of pumping water in a given area equal or exceed the fixed costs of drilling plus the variable costs of pumping. When ownership of the land is fragmented and users profit privately from extraction, however, wells may be drilled in closer proximity as landowners compete to access ground water.

Framework for Analyzing Aggregate Benefits of Pumping Controls

Consider land overlying an aquifer that could be broken into n parcels, $i = 1,2, \ldots, n$. For simplification we assume there is a low fixed cost to drilling, so wells can exist on all potential parcels. Each well has a net benefit function, $\pi_i(w_i, h_i)$, where revenues are increasing in a concave manner in the amount of water pumped, w_i, and costs decrease with the height of the water table, h_i, and increase with w_i. Rapid pumping at one well can cause water to flow towards the pumper's parcel from neighbors, effectively lowering their water levels. Resource movement away from well i is modeled as follows: the flow to other users, $-i$, is $\theta(h_i(t) - h_{-i}(t))$, where the transfer coefficient θ is a hydrological constant determined by aquifer rock. If $h_{-i}(t) > h_i(t)$, the entire expression is negative and water flows from $-i$ to i.

With multiple owners, water is pumped according to individual owner benefits. Without governance controls, user i maximizes an individual value function, V_i, by choosing the pumping path w_{it} that is the solution to the problem:

$$V_i^0 = \max_{w_i} \int_0^{\infty} \pi_i(w_i, h_i) e^{-\delta t}\, dt$$
$$s.t. \quad \dot{h}_i = r_i - w_i - \theta(h_i - h_{-i}) \tag{1}$$

where time arguments have been suppressed to simplify notation. The state equation shows that the change in the elevation of water is equal to local recharge, r_i, minus water extracted by the user on parcel i, w_i, minus the water that flows away from i. If i is a net recipient of water, inflow increases local water table elevation.

For a sole owner, the pumping decision includes all the parcels. For instance, if parcels are too closely spaced, the sole owner can choose not to extract water from certain parcels. The dynamic optimization problem for the entire basin is:

$$V^M = \max_{\{w_i\}_{i=1}^{n}} \int_0^{\infty} \sum_{i=1}^{n} \big(\pi_i(w_i, h_i)\big)\, e^{-\delta t}\, dt$$
$$s.t. \qquad \dot{h}_i = r_i - w_i - \theta(h_i - h_{-i}), \qquad i = 1, \dots, n \tag{2}$$

where V^M is the value of all pumping over time. The sole owner chooses the rate of pumping for every parcel, w_i^*, that solves this problem. The owner fully internalizes all well externalities and maximizes the private rental value of the reservoir. Additional insight is gained by using Darcy's law to approximate the movement of water under a hydraulic gradient, where:

$$\theta = \frac{k}{d}$$

and k is hydraulic conductivity, the rate at which water can move underground. The gradient is, in part, determined by d, the distance between parcel i and other extractors.

Most groundwater basins, however, are exploited by multiple surface owners with potential cross-well externalities. The benefits of governance institutions are maximized where they mimic the behavior of a sole owner. Therefore, it is useful to compare the solutions to Eqs. (1) and (2). The first-order condition for aquifer level, h, and extraction, w, for each parcel i under open access conditions is:

$$\frac{\partial \pi_i}{\partial w_i} = \frac{1}{\delta}\left(\frac{\partial \pi_i}{\partial h_i} - \frac{\partial \pi_i}{\partial w_i} \cdot \frac{k}{d}\right), \qquad (3)$$

while the condition for optimal management is:

$$\frac{\partial \pi_i}{\partial w_i} = \frac{1}{\delta}\left[\frac{\partial \pi_i}{\partial h_i} - \frac{k}{d} \cdot \left(\frac{\partial \pi_i}{\partial w_i} - \frac{\partial \pi_{-i}}{\partial w_{-i}}\right)\right] \qquad i = 1, \ldots, n. \qquad (4)$$

Delta represents the discount rate from the initial value function equations. Eqs. (3) and (4) represent the equalization of marginal benefits of pumping with private and social costs, respectively. Due to the concavity of the profit function with respect to pumping, the larger right-hand side expression in Eq. (4) implies a lower rate of pumping under a sole owner, than that under open access, reflected in Eq. (3).

We express the aggregate gains from adopting management as the sum of the differences in the individual value functions under open-access versus a socially optimal pumping regime. The present-value of profits for any parcel i under competitive pumping are V_i^0, the value obtained when conditions in Eq. (3) are implemented, and aggregate profits under open access are $V^0 = \sum_i V_i^0$. The maximum value provided by a pumping-control regime characterized by Eq. (4) is V^M, where $V^M \geq V^0$. Let $\Delta_i = V_i^M - V_i^0$ be the gain or loss of profits in parcel i with governance relative to open access. Although aggregate welfare is increased under management, individuals may gain more or less, depending upon their reservoir placement if water tables, conductivity, well-density, recharge, and water values vary.

We introduce 5 predictions regarding which users benefit more from strict controls and hence are more likely to support the definition of groundwater rights:

i. *For otherwise identical users i and j, if* $\mathrm{k}_i > \mathrm{k}_j$, *then* $\Delta_i > \Delta_j$.

ii. *For otherwise identical users i and j, if* $\mathrm{r}_i > \mathrm{r}_j$, *then* $\Delta_i < \Delta_j$.

iii. *For otherwise identical users i and j, if* $\mathrm{d}_i > \mathrm{d}_j$, *then* $\Delta_i < \Delta_j$.

iv. *For otherwise identical users i and j, if* $\frac{\partial \pi_i}{\partial w_i} > \frac{\partial \pi_j}{\partial w_j}$, *then* $\Delta_i > \Delta_j$.

Finally, low water tables impose an additional cost on users, f_i, due to seawater intrusion or subsidence. If the benefit function includes this term, $\pi_i(w_i, h_i, f_i)$ where benefits are decreasing in f_i then:

v. *For otherwise identical users i and j, if* $f_i > f_j$, *then* $\Delta_i > \Delta_j$.

All told, individual benefits of strict controls increase, *ceteris paribus*, with hydraulic conductivity, aridness (lack of recharge), local well density, the individual's marginal product of water, and exposure to collateral effects, such as subsidence.

Framework for Analyzing the Transaction Costs of Implementing Pumping Controls

Even when there are *aggregate* net benefits from implementing management regimes that constrain individual pumping, not all parties perceive individual net gains. Therefore, some may resist collective action. In this event, management regimes may not be adopted, be adopted late, or be modified with more limited constraints. As an example, consider the disparate value positions faced by urban water utilities and farmers. Utilities tend to have longer planning horizons and a higher marginal product of water than do agricultural users. As a result, they will benefit more from management structures that keep water levels high and ensure long-term resource access. In contrast, farmers prefer the flexibility of groundwater pumping and benefit from drawdown when surface water sources are limited during drought.

Institutional factors also play a major role. In California, agricultural users typically hold high-priority correlative groundwater rights, while urban utilities have subordinate appropriative rights. Basin adjudication for formal groundwater rights sometimes leads to restrictions on individual pumping and a flattening of the priority hierarchy. Accordingly, basins with a larger mix of agricultural and urban users will have higher transaction costs in adjudication efforts than will those where either type dominates, all else equal.

We posit an explicit form of transaction costs, C, that inhibit the formation of formal management institutions. Let total benefits of pumping controls be the sum of individual gains or losses: $\Delta = \sum \Delta_i$. Generally, action to implement extraction restrictions will be undertaken when $\Delta \geq C$. Transaction costs take the form

$$C = g\big(v(\Delta_i)\big), \tag{5}$$

where $v(\cdot)$ is a function of the dispersion of Δ_i, such as aggregate variance, $v(\Delta_i) = \sum_{i=1}^{N}(\Delta_i - \mu_\Delta)^2$. The function $g(\cdot)$ is monotonically increasing in the dispersion of the Δ_i's.

Based on this analytic framework, we add three additional predictions. In comparing two basins that are otherwise identical:

vi. *Basins with a larger number of users are less likely to have stronger pumping controls.*

vii. *Basins with more heterogeneity in pumper benefits, Δ_i, are less likely to have stronger pumping controls.*

viii. *Larger basins are less likely to have stronger pumping controls.*

Prediction (viii) follows because large basins generally have more pumpers, greater hydrological variation, higher measurement costs, and greater disparity in pumper assessments of benefits.

IV. Data

Data on basin and user characteristics were collected for 445 basins as shown in Table 1. Variable details are in Appendix A. Mean annual precipitation and its spatial variance are constructed from historical precipitation data from Oregon State University's PRISM Climate Group. Data on other physical attributes of basins are compiled from California Department of Water Resources (DWR) data. Basin boundary shapefiles are from DWR, and GIS is used to compute the relevant statistics. A coastline dummy is equal to 1 if the basin's boundary touches the coast at any point. Well yield, a measure of physical capacity that does not depend on well size or type, proxies for hydraulic conductivity and is available from DWR for 197 basins. County-level farm statistics are from USDA Agricultural Censuses. The number of farms is calculated as an average over the period 1940-1959 to capture the period during which center-pivot irrigation was introduced but before adjudications went into effect, which limits endogeneity concerns. Urban population numbers are from the California Department of Finance, and urban growth rates are calculated for 1950-2010. Finally, whether a basin has a State Water Project (SWP) connection for supplemental surface water is determined by the authors (Appendix A). State Water Project connections to a basin provide alternative surface water, potentially lowering the benefits of groundwater extraction controls. On the other hand, such connections often are provided in areas with high water values due to urban population growth.

The dataset also includes the number of wells in a basin, the proportion by use category, and the proportion within 1000m of the coast. These are calculated from well-completion reports collected by DWR. In addition, well heterogeneity is defined as $(\% \, Non - ag \, wells) \times (\% \, ag \, wells)$, and the variable ranges from 0 to .25. Well data for number of wells, types, and related spatial statistics are incomplete for 31 basins, primarily in the San Joaquin Valley. To address this problem, we first drop all basin observations with missing well data, but doing so may introduce bias if missing data are not random. Second, we use a multiple imputation procedure, whereby we regress the variables for which there are missing values, drawing from complete observations, on all covariates in the analysis. The estimated coefficients are used to generate distributions of the number of wells, agricultural wells, and wells near the coast, and then imputed values are drawn for the relevant 31 basins (Appendix B). From these imputed values we calculate well density and the necessary proportions of user types.

Table 1: List of Variables

Variable	Units	Source
Mean Precipitation (1950 - 2014)	Millimeters (100s)	*PRISM*
Precipitation Spatial Variance (1950 - 2014)	Millimeters (100s, squared)	*PRISM*
Basin Surface Area	Acres (1000s)	*DWR/Author*
Coastline Dummy	Dummy	*DWR/Author*
Well Yield	Gal/min	*DWR*
Number of Farms (1940-1959)	Count (100s)	*USDA*
Number of Wells	Count (100s)	*DWR*
Agricultural/Non-Agricultural Wells	Count or Percentage	*DWR*
Well Density	Count/Acre	*DWR/Author*
Number of Wells within 1000m of Coast	Count or Percentage	*DWR/Author*
Well Heterogeneity	(% Ag) x (% Non-Ag)	*Author*
Urban Population Growth (1950 - 2010)	Average Decadal Growth Rate	*CA. Dept of Finance/ Author*
State Water Project Connection	Dummy	*Author*
Number of GMPs	Number	*DWR*
Adjudication of Groundwater Rights	Dummy	*Author*
Management Regime	Categorical	*DWR/Author*
Critically Overdrafted Basin	Dummy	*DWR*
Length of Adjudication Process	Years	*Author*
GMP Fragmentation	Ratio	*DWR/Author*

In our analysis of the benefits of pumping constraints, the dependent variable identifies which regime has been adopted: no constraint, GMP (as designated by the DWR), or adjudication. Basins are assigned a value: (1) if they have no GMP or property rights adjudication; (2) if the basin has at least one GMP, but no adjudication; or (3) if the basin has been adjudicated.

V. Benefits and Determinants of Collective Action

A. Empirical Strategy

Given our discussion of the varying costs of implementing pumping controls of increased stringency, we infer latent benefits Y_i^* for groundwater basin i from observed choices: (1) no controls, (2) GMPs, or (3) property rights adjudication. We estimate latent benefits via an ordered logit model.

Consider a vector of n characteristics, X_i. The benefits of collective controls to mitigate open-access losses are described by the following relationship:

$$Y_i^* = X_i'\beta + u_i,$$

where u_i is assumed to be distributed standard logistic. Now we define Y_i as the level of management, where $Y_i = \{1,2,3\}$ represents {No controls, GMP, Adjudication}. The value of Y_i is determined by the unobserved latent variable Y_i^* according to the following:

$$Y_i = 1 \; if \; Y_i^* < \kappa_1$$

$$Y_i = 2 \; if \; \kappa_1 \leq Y_i^* < \kappa_2$$

$$Y_i = 3 \; if \; \kappa_2 \leq Y_i^*,$$

where κ_1 is the cost of implementing a GMP, κ_2 is the cost of adjudicating property rights, and $\kappa_1 \leq \kappa_2$. It is costlier to adjudicate than to agree on a GMP. The parameters $\hat{\kappa}_1, \hat{\kappa}_2, \hat{\beta}_1, \hat{\beta}_2, \ldots, \hat{\beta}_n$

are estimated by maximum likelihood. The $\hat{\beta}$ estimates indicate how a variable increases or decreases the benefits of pumping controls, and the $\hat{\kappa}$ estimates indicate different average regime costs.

B. Collective Action Benefits Estimation Results

We are interested in identifying the characteristics of basins that would most benefit from pumping controls. After that, we analyze why agents in those basins adopt strict management or fail to take any action.

Table 3 presents predicted signs for the estimated coefficients in the ordered logit regression. Well yields (a proxy for hydraulic conductivity), well density, exposure to seawater intrusion, and increases in the relative value of water induced by urban population growth raise the benefits of adopting management of any type. Greater precipitation supports groundwater recharge and reduces the benefits of controls on pumping. State Water Project connections to a basin provide alternative surface water, potentially lowering the benefits of groundwater extraction controls. The variable, however, is highly correlated with water value (and urban population growth). Accordingly, the predicted sign of the variable is ambiguous.

Table 3: Empirical Predictions for the Basin Benefits of Management – Ordered Logit

Measure	Predicted Sign	Prediction from Analytic Model
Well Yield	+	i
Precipitation	-	ii
State Water Project Dummy	-/+	ii/iv
Coastline Dummy	+	v
Well Density	+	iii
Urban Growth	+	iv

The results of various specifications are shown in Table 4. Some specifications include the conductivity measure, well yield, but it is available only for 185 basins (197 if the San

Joaquin is broken up into its constituent subbasins). Other specifications exclude basins with imputed well data. Columns 1-6 report estimates for an ordered logit across the three types of management, while columns 7 and 8 reflect a standard logit regression where GMP and adjudicated basins are grouped together as “managed” basins, allowing us to relax the assumption of tiered management stringency.[9] Columns 1 and 2 reflect a baseline specification that includes all of the variables with management benefit predictions.[10]

Across all specifications, the findings are broadly consistent with model predictions (i)-(v) in Section III.[11] Well yield or conductivity is positive and statistically significant in 3 of 4 specifications, urban population growth as a proxy for value is highly significant in all specifications, and well density is always positive although its significance is sensitive to the inclusion of imputed data. Precipitation has significantly negative effects in 4 specifications, while its sign depends on the inclusion of well yield. State Water Project connections seemingly proxy for water value, with the estimated coefficient large, positive, and statistically significant. The results are robust to its inclusion.[12]

Table 5 presents estimates of the marginal effects of the results shown in Table 4, column (2). The marginal effect of increasing urban growth leads to the greatest change in probability of adopting stricter pumping controls: a one standard-deviation change increases the probability of

[9] The ordered logit model relies on a parallel slopes assumption, i.e., that the coefficient estimates in binary logit models between None and GMP and GMP and Adjudication are statistically similar. This assumption can be assessed using a Brant Test. We fail to reject this assumption at the 5% level for our main specifications.
[10] In all columns the San Joaquin Valley groundwater basin is broken into its constituent subbasins because it is by far the largest aquifer in the state as well as one of the most important for agriculture, and treating it as a singular basin may mask important heterogeneity.
[11] We also include two robustness checks in the Appendices. We agglomerate the San Joaquin subbasins into one basin and present the results (Appendix D). In addition, other regression specifications including our SWP variable are included (Appendix E). The results remain broadly consistent with those reported here.
[12] The estimated coefficient on the coastline dummy is consistently negative, although not statistically significant. This result is likely due to the fact that coastal basins have higher transaction costs in reaching agreement as pumpers near the coast and exposed to seawater intrusion have different incentives for controls than do inland pumpers, who are less impacted.

Table 4: Basin Benefits of Management

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
			Ordered Logit				Logit	
	Mgt Type	Mgt Type	Mgt Type	Mgt Type	Mgt Type	Mgt Type	Mgmt	Mgmt
Avg. Well Yield	0.000487	0.000516*			0.000579**		0.000624*	
	(0.000297)	(0.000306)			(0.000290)		(0.000359)	
Mean Precipitation 1950-2014	0.00394	-0.0353	-0.0898***	-0.110***	0.0499	-0.0507*	0.0157	-0.0829***
	(0.0480)	(0.0506)	(0.0288)	(0.0295)	(0.0499)	(0.0287)	(0.0569)	(0.0299)
Well Density	196.8	5,099***	2,770	7,070***	400.2	2,273	436.3	3,350
	(575.0)	(1,580)	(2,536)	(1,795)	(735.6)	(2,196)	(860.3)	(3,490)
Average Urban Pop. Growth (1950-2010)	0.0326***	0.0282***	0.0285***	0.0234***	0.0243***	0.0198***	0.0540***	0.0331***
	(0.00839)	(0.00802)	(0.00575)	(0.00550)	(0.00896)	(0.00599)	(0.0206)	(0.00982)
Coastline Dummy	-0.305	-0.763	-0.255	-0.283	-0.820	-0.685	-0.665	-0.339
	(0.448)	(0.525)	(0.378)	(0.398)	(0.560)	(0.426)	(0.488)	(0.382)
State Water Project Connection					1.428***	1.690***		
					(0.388)	(0.313)		
Kappa 1/Constant	0.910***	0.890**	0.710***	0.701***	1.423***	1.098***	-1.113***	-0.766***
	(0.346)	(0.346)	(0.168)	(0.176)	(0.362)	(0.180)	(0.358)	(0.171)
Kappa 2	3.008***	2.714***	2.713***	2.552***	3.677***	3.258***		
	(0.467)	(0.449)	(0.281)	(0.275)	(0.460)	(0.271)		
Observations	197	166	445	400	197	445	197	445
Missing Basins	Imputed	Dropped	Imputed	Dropped	Imputed	Imputed	Imputed	Imputed

Notes: Robust standard errors in parentheses and significance levels are: *** p<0.01, ** p<0.05, * p<0.1. The number of observations is determined as follows: The entire data set is 445 observations, and 45 observations are dropped when list wise deletion is implemented. If well yield is included, the dataset collapses to 197 observations due to missing values, and listwise deletion further reduces the number of observations to 166.

falling into the adjudicated category by 4.70 percentage points and of adopting a GMP by 8.17 percentage points. The effects of well yield and density are of slightly smaller magnitude. The underlying probability of adjudicating groundwater rights is around 9% and of having a GMP around 29%. Accordingly, the magnitude of changing these variables by a full standard deviation on adoption of adjudication or a GMP is substantial relative to these underlying probabilities.

Table 5: Marginal Effects of Key Variables on Adoption of Groundwater Management

	Average Well Yield	Well Density	Average Urban Growth
One Standard Deviation around Mean			
None	-7.23%	-5.29%	-12.87%
GMP	4.56%	3.40%	8.17%
Adjudication	2.67%	1.88%	4.70%

Indeed, the observables that we associate with higher benefits are widespread in the basins that have adopted the most stringent management via definition of groundwater rights. Consider the adjudicated basins in eastern Los Angeles: water is scarce due to low recharge (an average of 403 mm (15.86 in)/year compared to the sample mean of 497 mm (19.57 in)/year), high urban population growth rates (42% on average, compared to a sample mean of 8%), a mean of average well yields (965 gal/min) above the sample mean (561), and high well densities.[13]

High expected aggregate benefits alone, however, may *not* be enough to lead to agreement for collective action if the agents have divergent views on the benefits. The Oxnard Plain to the west shares many basin characteristics with those in eastern Los Angeles, but users

[13] Here we include the following adjudications: Main San Gabriel (1968-73), Puente (81-85), Six Basins (96-98), Chino (75-78), Western San Bernardino (63-69), and Beaumont (2002-04).

have not agreed upon pumping restrictions. Accordingly, we turn now to examining the determinants of transaction costs that impede collective action.

VI. Transaction Costs in Collective Action to Constrain Pumping

A. Empirical Strategy

The effect of transaction costs in molding group responses to open-access losses is examined in three ways:

First, we examine critically overdrafted basins as defined by Department of Water Resources to determine why pumpers have not implemented controls. To do this, we explore which transaction cost variables explain a lack of collective action in those basins that would seem to need the strictest controls, relative to those basins that have adjudicated property rights. We show how the determinants of transaction costs systematically differ across the two.

Second, we use a duration variable to examine transaction costs among adjudicated basins. From the time that court documents are filed by adjudication proponents to the finalization of the stipulated judgement assigning groundwater rights, pumpers bargain over the implied assignment of property rights. When judgements are appealed or important parties remain recalcitrant, the process is drawn out and additional costs are incurred.

Third, where users have chosen not to pursue adjudication of property rights, but still recognize the need for management via GMPs, we analyze why many of those are fragmented. Where agreement on management institutions remains elusive among heterogeneous parties, different groups form their own management districts, resulting in a patchwork of small GMPs across the basin.

B. Comparison of Critically Overdrafted and Adjudicated Basins

Critically overdrafted basins are identified as those where maintaining current pumping rates likely will result in significant adverse effects.[14] We use estimated values from the ordered logit results in Table 4 to demonstrate that the critical and adjudicated basins are comparable in the aggregate benefits of pumping controls. Although there are 20 critical basins, 3 have been recently adjudicated in part or in whole. Accordingly, 17 basins are coded as critical; these and the remaining 31 adjudicated basins form a sample size of 48. Nine of these, however, lack well yield data, leaving us with 39 basin observations for this comparison. We predict a management benefits value using average well yield, well density, average precipitation, a coastline dummy, and the average decadal urban population growth rate from 1950 to 2010 (column 1, Table 4). We then estimate $V_i = \beta_0 + \beta_1 * Adjudicated_i + u_i$, where the coefficient β_1 captures the difference in conditional means between adjudicated and critical basins for modeled benefits V_i. The results are shown in column 1, Table 6.

Table 6: Differences in Aggregate Benefits of Pumping Controls and Transaction Cost Variables between Critical and Adjudicated Basins

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Modeled Benefits	Basin Size	Number of Wells	Log Number of Wells	Well Heterogeneity	Spatial Var Precip	SWP Connection
Adjudicated Basins	-0.486	-311.3**	-20.00	-1.655**	-0.0144	0.0340	0.421***
	(0.291)	(120.4)	(42.77)	(0.770)	(0.0303)	(0.122)	(0.141)
Constant	1.632***	493.3***	28.51	5.810***	0.143***	0.271**	0.353***
	(0.123)	(111.1)	(43.20)	(0.598)	(0.0264)	(0.101)	(0.118)
Observations	39	48	48	48	48	48	48

Our average index of the benefits of adopting pumping constraints is over 40% *higher* in the critically overdrafted basins than it is in adjudicated ones, which reinforces the relevance of this empirical test: if the benefits of curtailing excessive pumping are so high in these critical

[14] A detailed definition of critical overdraft can be found here: http://www.water.ca.gov/groundwater/sgm/cod.cfm.

basins, why have they not adjudicated property rights? To assess the impact of transaction cost variables, we turn to predictions (vi)-(viii) from Section III regarding the effect of basin size, the number of users, and heterogeneity in pumpers and the resource. We estimate the same equation as in column 1, but with transaction cost variables, and predict that these variables are systematically higher in critical basins. The results are shown in columns 2-7, Table 6.

As predicted, critical basins are systematically larger with more users (wells), and the users are more heterogeneous in their demand for or valuation of water relative to the adjudicated basins. The latter are more likely to have imported water connections, which is consistent with the notion that imported water lowers the costs of adjudication.[15] All in all, it is clear that in critically overdrafted basins, users face higher transaction costs that block agreement on the pumping constraints that have been implemented in adjudicated basins.

The impact of these transaction cost variables is particularly clear in one critical basin, Borrego Valley, where groundwater is effectively the sole source of water and water tables have declined over 100 feet in recent decades. Users have implemented one GMP, but it has proved ineffectual. Borrego Valley is almost twice as large as the sample mean (152,560 acres relative to 89,000), and its mixed pumpers (municipal and agricultural users in addition to golf courses and a state park) greatly differ in water valuation. Well heterogeneity in Borrego Valley is .16, much higher than the sample average of .06.

C. *Transaction Costs in the Adjudication of Groundwater Rights*

To further understand the role of transaction costs in collective action, we examine how long it takes to reach agreement on a property rights distribution in basins when it has occurred. Adjudications vary significantly in the time it takes to concur on the assignment of groundwater

[15] This prediction of the effect of imported water on the transaction costs side can be supported anecdotally from the cases in the Central and West Basins. Imported water lowers transaction costs by allowing users recharge rather than restricting pumping. Where the costs of reductions are very high, this may be more efficient and ease agreement.

property rights. Parties disagree on the level of allowable pumping, where basin depletion is greatest, the risk of collateral effects, and the division of shares over the total allowable extraction. If some pumpers are not affected by seawater intrusion, lie on thick portions of the basin with low conductivity, have different water valuations, or are not impacted by high well density, then they may accept the *status quo* and resist assignment of more formal groundwater rights that do not incorporate these advantages. Basin size raises the number of pumpers and the costs of obtaining and agreeing on reliable hydrologic information (Donohew, 2005).

An example of a particularly lengthy adjudication process is the Santa Maria Valley basin. Pumpers began adjudication proceedings in 1997; they broke down in 2008 and finally were completed in 2013. The groundwater basin is relatively large, has a large number of users (the number of wells is 5 times the sample average), and has a mix of municipal and agricultural users; in addition, coastal pumpers are more affected by seawater than those inland. These conditions engendered a lengthy, contentious litigation process with total costs of $11 million (Cal Coast News, 2013).

Figure 2 presents the temporal distribution of 25 adjudications in California and their durations.[16] The mean adjudication duration is 8 years, and the standard deviation is 5.8 years. To examine how the length of adjudication is affected by transaction costs, we conduct duration analysis focusing on how many basins remain in adjudication each year after the process begins. Due to the low number of observations, we present nonparametric Kaplan-Meier estimates of the survivor function and investigate how they vary according to the same transaction cost variables

[16] Throughout the text, we list 31 adjudicated basins, resulting from 25 adjudication decisions. Some adjudication decisions apply to multiple basins as defined in DWR's Bulletin 118 (2004), which we use to define our basin observations.

we examine above.[17] Factors increasing transaction costs lead to a lower hazard rate, which in turn implies a higher survival function or longer expected adjudication duration. Kaplan-Meier survival functions are stratified into two groups: basins that exhibit values below the median for each transaction cost variable and those basins above the median.

Figure 2: Groundwater Adjudication Chronology

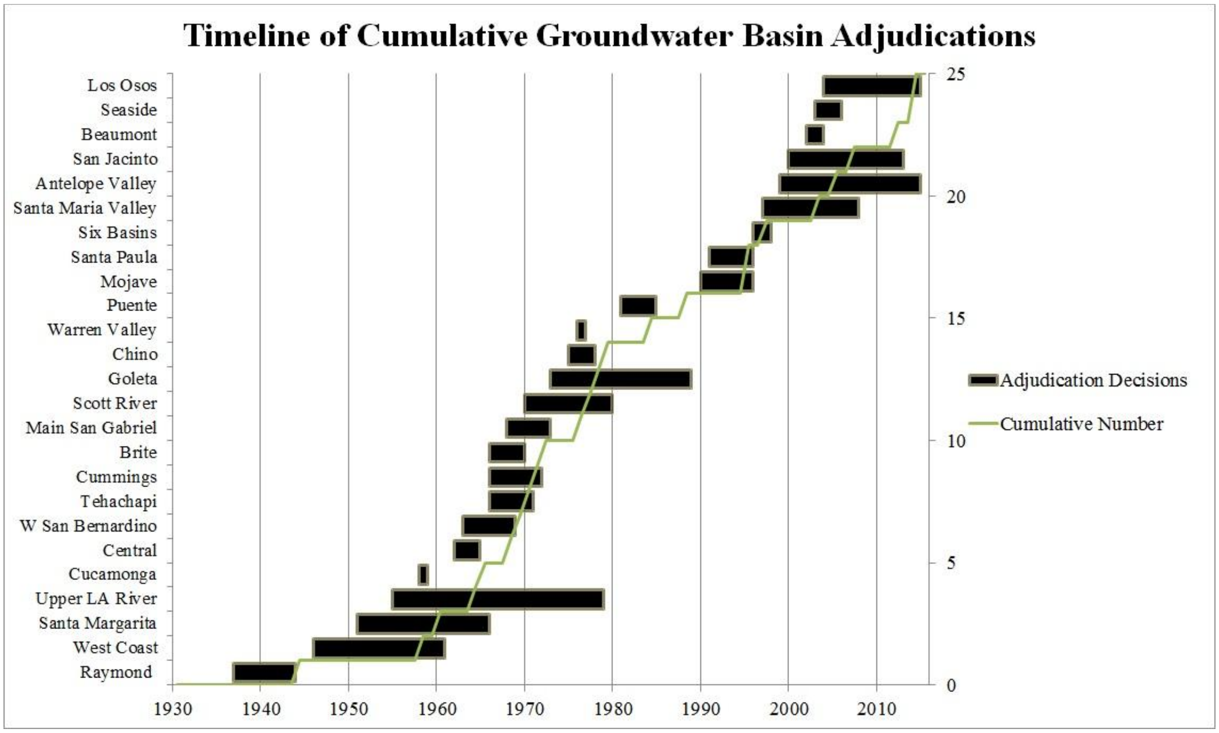
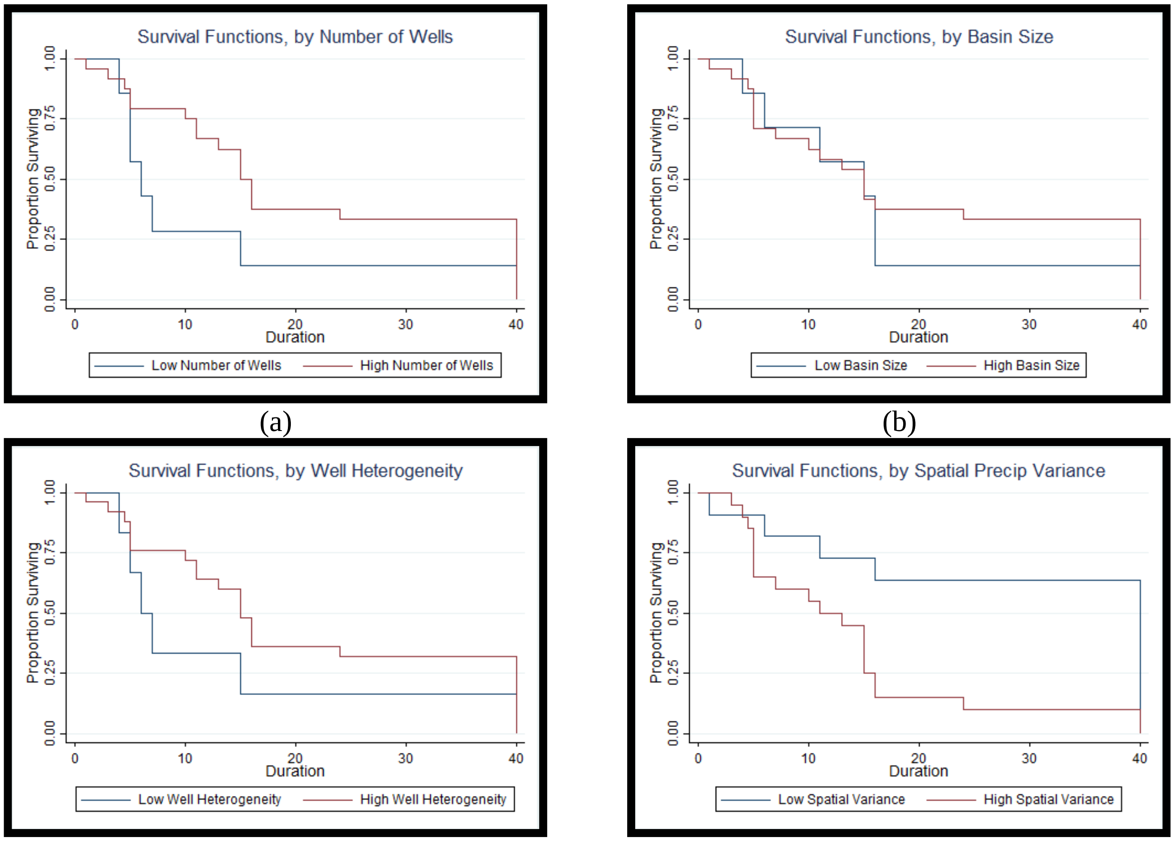


Figure 3 presents the plotted survival functions. The red lines correspond to observations above the sample median for: (a) numbers of wells, (b) basin size, (c) well water use heterogeneity, and (d) spatial precipitation variance. The number of wells and well heterogeneity

[17] In Appendix C we report results from a Cox Proportional Hazard (Cox PH) Model, which controls for all covariates simultaneously and attempts to capture the marginal effect of any particular covariate on the length of adjudication processes. The Cox PH results are illustrative of the conditional effects of each variable. They are identified from very few observations, so we prefer the nonparametric estimates here.

especially are associated with lengthier and costlier adjudications, and the effect is conspicuous across the observed range of adjudication durations.[18]

Figure 3: Results – Nonparametric Duration Analysis of Property Rights Allocation



(a) (b) (c) (d)

D. Fragmentation of Groundwater Management Plans

When parties cannot agree on a basin-wide groundwater management plan, partial ones, covering only portions of the basin may emerge to encompass a more homogeneous group of pumpers. To examine the relationship between transaction costs and observed GMP design, we present the following measure of GMP fragmentation for each basin i: $\frac{Basin\ Size_i}{Mean\ GMP\ Size_i}$. This measure captures how many GMPs of the average size in that basin it would take to cover its

[18] Counter to our expected result, high spatial variance in precipitation is associated with faster adjudications and there is no clear effect of basin size. Results for the parametric Cox PH model are given in Appendix C and indicate that basin size, spatial variance in precipitation, and well location near the coast do increase duration.

entirety. Using all groundwater basins with GMPs, we estimate $Y_i = X_i'\beta + u_i$, with GMP fragmentation as the dependent variable. The results are reported in Table 7.

Table 7: Results – GMP Fragmentation and Bargaining Costs

GMP Fragmentation	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Basin Area (acres)	0.00967***						0.00743***
	(0.000864)						(0.00256)
Number of Wells		0.105**					0.0300
		(0.0407)					(0.0301)
Log Number of Wells			0.804*				
			(0.410)				
Well Heterogeneity				7.672			0.735
				(6.612)			(5.031)
Mean Spatial Precip. Variance 1950-2014					0.970		0.250
					(0.987)		(0.382)
Coastline Dummy						-1.269	-0.215
						(0.892)	(0.929)
Constant	1.637***	2.554***	0.437	2.627***	3.059***	3.528***	1.671***
	(0.349)	(0.410)	(1.235)	(0.584)	(0.448)	(0.597)	(0.437)
N	105	104	104	104	105	104	104

Notes: Robust standard errors in parentheses and *** p<.01, ** p<.05, and * p<.1. The number of observations is either 105 for the full sample or 104 where well numbers or types must be imputed and one observation is lost.

As in the other transaction cost exercises, the signs of the coefficients for basin size, the number of users, user heterogeneity and mean spatial precipitation variance (recharge differences) are positive in all specifications. While the small number of observations limits the statistical power, basin area is significant at the 1% level in both specification (1) and (7) and well number measures are significant when regressed individually. GMP fragmentation is more likely to occur in larger basins with more pumpers who differ in water valuation and where recharge varies.

E. Transaction Costs in Mitigating the Economic Losses of Groundwater Overdraft

Our empirical analysis of varying collective responses to competitive over-exploitation across California's 445 groundwater basins reveals that the more common the resource as indicated by well yield, the higher the value of water as indicated by urban population growth, and the greater the cross-well externalities as indicated by well density, the more likely basin users will adopt individual groundwater rights or implement GMPs. On the other hand, where precipitation is greater and there is more recharge, there is less need. Furthermore, transaction costs block agreement on what exactly remedies should look like: where the basin is larger with more users who are more heterogeneous, agents are less likely to agree upon groundwater rights or management plans, and rent dissipation continues. Even in critically overdrafted basins where property rights would be the most effective response, they are not adopted.

These findings reveal the role of transaction costs in impeding collective action among parties even when there are large aggregate gains from undertaking it. Users in critical basins encounter especially high costs in curtailing excessive exploitation. These basins are on average larger with a larger number of more different users than is the case in basins where parties have successfully agreed upon an allocation of property rights. In adjudicated basins, however, there is still variation in how long it takes for the parties to reach agreement, and this time varies according to the numbers of parties (wells), basin size, heterogeneity in water valuation, and variation in precipitation. If parties cannot agree on a property rights regime, they can turn to a groundwater management plan, but many of those cover only parts of the formation. Fragmentation of management plans also is more likely as basin size increases, as the number of users grows, and as water values differ more greatly.

On the basis of these insights, basins in California can be described as belonging to three categories based on the make-up of their users:

1) Users in basins where gains from adopting management are low do not implement management despite relatively low transaction costs. A typical basin in this category

has a small number of agricultural users, high basin recharge, and no collateral impacts of drawdown.

2) Basins with mixed agricultural and urban users face high transaction costs. Increasing the proportion of the latter raises returns to adopting management, but a mix of user types raises transaction costs substantially.
3) In basins where all users value the resource highly, such as in urban settings, returns to management are high and transaction costs comparatively low, leading to adjudication of groundwater rights.

These three categories mirror the historical development of many adjudicated basins in California. When users were relatively few and focused on agricultural production, few perceived a need to restrict pumping. As demand grew and areas became more urban, the desire to control and regulate groundwater increased, but solving the problem was difficult. Only users who faced risk of collateral impacts, were densely settled, or urbanized very quickly chose to adjudicate early (e.g., West Coast (1946), Raymond (1937), or Upper LA River (1955)). Later, most of the remaining Los Angeles basin and surrounding areas were adjudicated as farm land was urbanized (e.g., Six Basins (1996), Main San Gabriel (1968), or Mojave (1990)).

More generally, the effective management of groundwater is a major natural resource challenge worldwide. The problems encountered in securing consensus on action to avoid serious economic loss that we document, however, are emblematic of similar obstacles found across many natural and environmental resources where sustainability is desired.

VII. Concluding Remarks: Transaction Costs and Collective Action

In 1960, Ronald Coase suggested that standard ways of viewing open-access problems as ones of externalities, correctable with Pigouvian taxes or regulation, were flawed. He recommended consideration of the reciprocal nature of any environmental/natural resource problem and the use of bargaining among the relevant parties to reduce exploitation. Coase explicitly recognized that transaction costs could be high and that they could impede a collective response: “Once the costs of carrying out market transactions are taken into account it is clear that such a rearrangement of rights will only be undertaken when the increase in the value of production consequent upon the rearrangement is greater than the costs which would be involved in bringing it about” (Coase, 1960, 15-16). Indeed, since Coase’s analysis, economists increasingly have acknowledged that the existence of costly open access resource management institutions alone is not sufficient to spur action. It is not only aggregate gains that matter; individual gains and losses from the adoption of controls, including the transaction costs of reaching agreement on the implicit assignment of property rights, determine whether or not a consensus can be reached. Despite growing awareness of the issue, however, it has been difficult to empirically examine transaction costs and how variation in them might affect collective action.

If collective action involves the mobilization of resource users for mitigation, then whether or not any user joins depends upon how they perceive their *status quo* position (present value of net returns) relative to what they would expect under the new arrangement—under a new, more formal property rights regime (present value of *ex ante* expected net returns). If the resource is large and heterogeneous in size and quality, then parts of it will exhibit open-access losses sooner than others and not all parties will observe this variation. Additionally, if the users are heterogeneous in production cost and value, then they will have different abilities to adapt to open access, different asset valuations, and different time frames for production. These sources of heterogeneity mean that some parties perceive individual open-access losses as more severe than do others and hence push for early and more complete action. Others feel less imperative, particularly if the response offers them less then they expect under existing conditions. Under these circumstances, the latter will have to be compensated by the former to be convinced to comply with any collective solution. This is the Coasean bargain, and if transaction costs are sufficiently high, the parties may not be able to complete it and the open-access problem will persist.

In this paper, we examine user and resource characteristics (including production heterogeneity) that affect reactions to the common pool. The extensive variation in groundwater overdraft status and management in California, including open access, limited (and in important cases, fragmented) groundwater management plans, and fully adjudicated basins with defined property rights (varying in implementation time) provides a laboratory for investigating the sources and impact of transaction costs. Our analysis reveals why some groundwater basins have been more and others less amenable to collective responses to overdraft. Analysis of this particular case, made possible by our novel dataset, allows us to make discussion of transaction costs concrete and to identify specific resource and user characteristics that affect the benefits and success of implementing collective remedies to the common pool.

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IX. Data and Results Appendices

A. Data Definitions

Mean Precipitation

Precipitation variables were calculated directly from PRISM interpolations using GIS software, and only precipitation falling over the basin itself, as defined in DWR's Bulletin 118, was included. These basin boundaries were obtained from DWR shapefiles.[19] The mean value from 1950 to 2014 was calculated.

Spatial Variance in Precipitation

Using the same PRISM data, the zonal statistics tool in ArcGIS was used to calculate the spatial variance in precipitation in each basin for each year, 1950-2014. The average level of variance was calculated for each basin.

Number of Farms

The number of farms is calculated as an average over the period 1940-1959 to capture the period during which center-pivot irrigation was introduced but before adjudications went into effect, which limits endogeneity concerns. These data are available historically from the USDA Agricultural Census on a county basis. When basins cover only portions of or multiple counties, the percentage of agricultural land within each county that was within each individual basin was computed using Cropscape data[20] from 2007, the earliest year for which data are available. Then, those proportions were used to assign the farms in each county to individual basins.

Basin Size

Basin size is a measure of the surface area overlying the aquifer. This was calculated using geometric calculations in GIS software, and the Albers Equal Area Conic projection was used to maintain area relations.

Coastline Dummy

The coastline dummy is equal to 1 if the boundary of the basin's polygon in the GIS shapefile touches the coast at any point.

Number of Wells

Well completion reports were provided by DWR, and these reports were imported into GIS software using latitude and longitude coordinates. The number of wells refers to the

[19] https://gis.water.ca.gov/app/gicima/
[20] https://nassgeodata.gmu.edu/CropScape/

number of wells physically located within a basin. With some exceptions, well completion reports place wells at the center of a township and range, i.e., all or most wells within a 6 mile by 6 mile grid have the same coordinates, so there may be some slight measurement error in this variable. One important note is that one can filter well completion reports by the date of well completion: we count only wells completed by the time adjudication began for adjudicated basins or 1980 for GMP or unmanaged basins (initial legislation governing the GMP process was adopted in 1980). This allows us to allay concerns that the implementation of management endogenously affects the number of wells or users.

Well Density

Our measure of well density simply divides the total number of wells in a basin by the size of the basin, in acres, as calculated using GIS software.

Number of Agricultural Wells/Non-Agricultural Wells

The number of wells by use type was calculated using planned use codes contained in the data. Specifically, any well listed with a planned use of irrigation, agricultural use, or animal or stock watering was counted as an agricultural well. All other planned uses were non-agricultural, including drinking water wells and injection wells. These numbers were calculated using the same date filters as used for the total number of wells. Proportions were calculated using the total number of wells.

Number of Wells within 1000m of the Coast

A 1000m-buffer was placed along the coastline, and the number of wells within this buffer within each basin was recorded. These numbers were calculated using the same date filters as used for the total number of wells. We then divide this by the total number of wells in that basin to come to our proportion.

Urban Population Growth

Historical census data for major municipalities were obtained from the California Department of Finance[21] and decadal growth rates for 1950-2010 were calculated. Then, if a city's center overlies a basin, that city's growth rate was included for that basin. City centers were located in GIS software using a point shapefile from USC's Southern California Earthquake Center.[22]

Well Heterogeneity

Our measure of well heterogeneity is defined as $(\%\ Non-ag\ wells) \times (\%\ ag\ wells)$, which reaches its maximum when agricultural and non-agricultural wells are evenly balanced.

[21] http://www.dof.ca.gov/Reports/Demographic_Reports/index.html#reports
[22] http://52.26.186.219/internships/useit/content/california-cities-point-shapefile

SWP Connections

Water agencies and irrigation districts holding *Table A* allotments from the State Water Project[23] were identified, and GIS shapefiles of water agencies in California[24] were used to identify basins underlying these water agencies. If a water agency holding an entitlement was not found in DWR's shapefile for GMPs, the authors located it on a map and judged which, if any, basins underlie its service area. If the service or management area of a water agency or irrigation district holding a SWP entitlement overlies an aquifer, that basin received a 1.

Number of Groundwater Management Plans

The number of GMPs overlying a basin was also calculated using the above-mentioned shapefiles from DWR. Any GMP polygon that intersects (i.e., overlaps) a basin was included in that basin’s tally.

Adjudication Dummy

This measure was based on previous research. If basin users have accepted a stipulated judgement and that judgement has been implemented following approval by a state court, then that basin was listed as adjudicated.

Adjudication Duration

Our calculated durations begin when court documents were first filed (as identified on subsequent judgement documents) and end when a judgement is reached by the court.

GMP Fragmentation

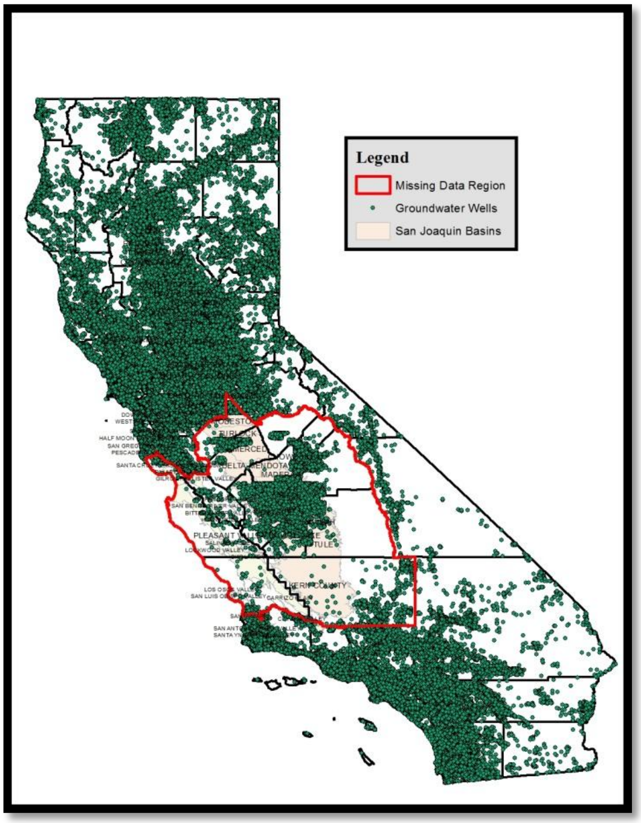
For each basin i we calculate $\frac{Basin\ Size_i}{Mean\ GMP\ Size_i}$. GMP sizes were calculated using the above-mentioned DWR shapefiles. This ratio captures how many GMPs of the average size in basin i it would take to cover its entirety. If basin users formulate several small GMPs, reflecting a high fragmentation of management, this measure will be high. It is always weakly greater than one.

[23] http://water.ca.gov/swpao/swp-max-table-a.html
[24] https://gis.water.ca.gov/app/gicima/

B. Missing Well Data and Multiple Imputation

Our well data are missing for some basins. Specifically, their locations are shown in Figure 4:

Figure 4: Spatial Representation of Well Data



Each green dot indicates one or more wells. Within the red area depicted on this map, well data are either completely or partially missing because the Fresno regional office of the DWR did not collect and digitize Well Completions Reports (WCRs) in the same manner as other regional offices (Senter, 2016). There are several methods for dealing with such missing data problems, two of which are listwise deletion and multiple imputation.

Multiple imputation is under most circumstances preferable to listwise deletion. This relates to the nature of the missing data mechanism, i.e., why the data are missing. If the data are missing completely at random, using listwise deletion (i.e., dropping those observations with missing data) results in unbiased parameter estimates. If, however, the missing data mechanism is endogenous to observed characteristics, listwise deletion will result in biased parameter estimates; multiple imputation on the basis of observable characteristics can resolve this bias. In the event that data are missing due to unobservable factors, multiple imputation may not remove all bias but will perform better than listwise deletion (Little and Rubin, 1987; Schafer, 1999).

Our missing data mechanism depends certainly on observable factors and likely also on unobservable factors. As a result, imputation will resolve some bias in estimation but not all of it because we cannot control for unobservable characteristics of the area covered by the Fresno regional office that may affect the number of wells, well density, etc. Still, the use of imputation can be justified on two grounds. First, the data are clearly not missing completely at random, so listwise deletion may produce severely biased results. Second, dropping the observations in this area would cost us many of the critically overdrafted basins in California, which in turn would severely hinder our analysis.

Schafer (1999) provides a useful overview of multiple imputation procedures. Multiple imputation proceeds in two major steps: 1) data imputation and 2) data analysis. In the imputation phase, a regression model is fit with the variable to be imputed as the dependent variable and every variable used in the analysis phase included on the right-hand side. In particular, one fits $X_{1i} = \mathrm{X}_{\mathrm{i}}'\beta + Y_i + \mathrm{u}_{\mathrm{i}}$, where X_1 is the explanatory variable to be imputed, X is of rank $K - 1$ (K being the number of explanatory variables in our analysis in aggregate), and Y is of rank J (where J is the number of dependent variables in our analysis in aggregate). In this way, parameters are estimated that allow for a conditional posterior distribution of the imputation variable of interest to be constructed, from which values are drawn for M imputations. The result is M “new” datasets that include different imputed values for all missing variables.

The second step, data analysis, involves using the M imputed datasets to perform the desired estimation for the research analysis. In particular, estimation is performed on each imputed dataset ($m = 1, \ldots, M$) individually, and then the parameter estimates from each imputation are combined according to rules designed by Rubin (1987). The end result is one set of parameter estimates derived from the existing data for all complete observations as well as the imputed data for incomplete observations, but all observations, both complete and imputed, are used in the analysis.

We impute three variables directly and another four as passive variables (i.e., as deterministic functions of imputed variables). Two variables, the number of wells and the percentage of wells in a basin used for agriculture, need to be imputed for 45 basins (when the San Joaquin is broken up into its constituent subbasins). The proportion of wells within 1000m of the coast is relevant only for basins on the coast and needs to be imputed for only 21 basins. Unfortunately, because well yield data are included in the imputation model, we are only able to impute values for 30 of the 45 basins and 17 of the 21 basins, respectively. However, we provide results with and without well yield to examine whether this issue affects our results.

After imputing values, we calculate four passive variables. The proportion of wells for non-agricultural use is defined as $(1 - \%Ag\ Wells)$. Well heterogeneity is defined as $(\%\ Ag\ Wells) * (\%\ Non - Ag\ Wells)$. Well density is calculated as $(Number\ of\ Wells)/(Basin\ Area)$. Finally, the proportion of wells within 1000m of the coast is squared to provide us with a quadratic term.

Then, we run our typical estimation using the ($M = 10$) datasets produced by the imputation process. We apply ordered logit, logit, and Cox PH models to the data, as described in their respective section. In order to recover conditional means in Section VI, we run OLS as well. For the purposes of the nonparametric duration analysis, we use averages of the imputed variables where necessary to construct dummy variables for high and low well counts as well as high and low well heterogeneity.

C. Cox Proportional Hazard Results

Formally, a Cox PH model can be represented as:

$$\lambda(t|X) = \lambda_0(t) * \kappa(X\beta')$$

where $\lambda(t|X)$ is the proportional hazard function, as a function of time conditional on the covariates. X is the vector of covariates[25] and λ_0 represents the underlying baseline hazard function. The parameter vector (β) is estimated using maximum likelihood and describes how the covariates affect the hazard rate after entry into the initial state.

We expect all coefficients of interest to have negative signs, increasing duration, save for the quadratic term on the proportion of wells near the coast—this effect is nonlinear and reduces bargaining costs at high proportions because bargaining positions again become more homogeneous. We test our predictions by estimating the coefficient vector and comparing the signs of the estimated coefficients with our predicted effects on bargaining costs.

Table 9 presents results from the Cox PH regressions on the duration of the adjudication process. We include several controls (number of farms, a coastline dummy, and the percentage of well types) because adjudication duration is not a perfect measure of bargaining costs:

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[25] In this case, $\kappa(\cdot)$ is not a function of time because we assume covariates are time-invariant.

adjudication duration may also be shorter when resource values are higher. Columns 1 and 2 use the imputed data in the baseline specification, while columns 3 and 4 drop the imputed observations. Columns 5 and 6 omit well yield to use the entire sample, and columns 7 and 8 control for any potential effect of imported water connections. Despite small sample sizes, we observe statistically significant results for several covariates.

Our strongest results concern basin size and the spatial variance in precipitation. Larger area increases the length of adjudications, and the coefficient estimates are highly statistically significant. Larger basins are generally more difficult to understand, and logistical costs are higher, leading to higher bargaining costs. This is one of the strongest predictors. The effect of high variance in precipitation has the same sign but is less reliably statistically significant. Meanwhile, coefficient estimates on well heterogeneity and the number of wells are also consistently negative although generally not statistically significant. When imputed observations are dropped, the proportion of users near the coastline in coastal basins also becomes statistically significant. That a higher proportion of wells within 1 km of the coastline increases the length of adjudication speaks to the difficulty of getting coastal users, who are exposed to seawater intrusion, and inland users, who are not, to agree on management rules. The sign and statistical significance on the quadratic term suggest that the effect is nonlinear: basins where a very high proportion of users are within 1 km of the coastline actually adjudicate quickly because bargaining positions are homogeneous.

As in the nonparametric duration analysis, imported water connections seem to have little effect. However, our controls present interesting results. Resource benefits seem to play a role because basins with many farms tend to adjudicate much more quickly, as aggregate benefits are higher.

Table 9: Bargaining Costs: Cox PH Results

Adj Duration	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Basin Area (acres)	-0.00391*		-0.0039***		-0.00225**		-0.00395*	
	(0.00218)		(0.00105)		(0.00106)		(0.00207)	
Mean Spatial Precip. Variance 1950-2014	-1.479*	-0.977	-1.656**	-1.189**	-0.0979	-0.0658	-1.491**	-0.995
	(0.756)	(0.636)	(0.674)	(0.601)	(0.475)	(0.477)	(0.726)	(0.645)
Avg. Well Yield	-0.000348	-0.000187	-0.000308	-0.000129			-0.000374	-0.000204
	(0.000408)	(0.000372)	(0.000326)	(0.000341)			(0.000413)	(0.000377)
Number of Wells (Exog)	-0.0585	-0.103	-0.0882**	-0.175***	-0.0226	-0.0530	-0.0594	-0.106
	(0.0670)	(0.0902)	(0.0359)	(0.0375)	(0.0338)	(0.0496)	(0.0685)	(0.0921)
Proportion of Wells within 1000m of Coastline (Exog)	-27.87	-25.33	-155.1**	-141.7**	-9.481	-8.905	-26.78	-27.15
	(66.86)	(50.03)	(74.86)	(62.10)	(32.20)	(26.15)	(68.40)	(53.70)
Proportion of Wells within 1000m Squared (Exog)	117.7	85.41	652.7**	567.4**	50.04	35.75	117.3	93.83
	(275.1)	(203.4)	(324.1)	(265.6)	(135.8)	(110.2)	(277.5)	(217.7)
Well Heterogeneity (Exog)	-8.489	-19.76	-20.44	-27.46	-5.296	-9.233	-8.705	-19.84
	(21.36)	(14.43)	(22.64)	(17.93)	(7.881)	(7.676)	(21.78)	(14.86)
State Water Project Connection							0.322	0.144
							(0.921)	(0.833)
Controls								
Coastline Dummy	0.216	0.567	1.405*	1.794***	0.235	0.408	0.0425	0.558
	(2.171)	(1.531)	(0.804)	(0.683)	(0.752)	(0.656)	(2.595)	(1.670)
Average Number of Farms 1940-1959	0.401***	0.263*	0.481***	0.401***	0.214***	0.162**	0.398***	0.266*
	(0.135)	(0.148)	(0.113)	(0.0883)	(0.0608)	(0.0792)	(0.131)	(0.147)
Percentage Ag Wells (Exog)	0.129	7.353	6.954	11.36	2.734	5.187	0.474	7.557
	(14.11)	(9.000)	(13.75)	(10.25)	(4.008)	(3.897)	(14.71)	(9.182)
N	23	23	21	21	31	31	23	23
Missing Basins	Imputed	Imputed	Dropped	Dropped	Imputed	Imputed	Imputed	Imputed

Notes: Standard errors in parentheses and * p<.1, ** p<.05, *** p<.01. The total number of adjudicated basins is 31; eight are lost when well yield is included, and another two when observations with imputed values are dropped.

D. Results with San Joaquin presented as one Basin

In this subsection we present the results of our ordered logit model when the San Joaquin groundwater basin is treated as one observational unit (instead of 15 subbasins). The results are broadly consistent with those presented in Section V.

Table 10: Benefits of Management – San Joaquin Whole

	(1)	(2)	(3)	(4)	(5)	(6)
	Ordered Logit				Logit	
	Mgt Type	Mgt Type	Mgt Type	Mgt Type	Mgmt	Mgmt
Avg. Well Yield	0.000507	0.000527*			0.000560*	
	(0.000319)	(0.000313)			(0.000336)	
Mean Precipitation 1950-2014	0.00747	-0.0346	-0.0751***	-0.108***	0.0208	-0.0748**
	(0.0465)	(0.0505)	(0.0266)	(0.0294)	(0.0554)	(0.0294)
Well Density (Exog)	30.18	4,990***	109.7	6,907***	697.8	3,254
	(110.2)	(1,564)	(332.9)	(1,748)	(1,190)	(3,289)
Average Urban Pop. Growth (1950-2010)	0.0314***	0.0282***	0.0252***	0.0221***	0.0449**	0.0248***
	(0.00932)	(0.00857)	(0.00603)	(0.00568)	(0.0205)	(0.00822)
Coastline Dummy	-0.309	-0.774	-0.0265	-0.252	-0.628	-0.224
	(0.415)	(0.522)	(0.332)	(0.396)	(0.509)	(0.365)
Kappa 1/Constant	0.957***	0.905***	0.762***	0.723***	-1.115***	-0.828***
	(0.345)	(0.347)	(0.168)	(0.177)	(0.351)	(0.171)
Kappa 2	2.738***	2.637***	2.535***	2.489***		
	(0.438)	(0.441)	(0.257)	(0.268)		
Observations	185	163	430	395	185	430
Missing Basins	Imputed	Dropped	Imputed	Dropped	Imputed	Imputed

Notes: Robust standard errors in parentheses and *** p<0.01, ** p<0.05, * p<0.1. The number of observations differs from those in Table 4 because the 15 San Joaquin subbasins are treated as one basin.

E. Benefits Results with State Water Project Connections

In this subsection we present the results of our ordered logit model when the dummy variable associated with imported water connections is included in every specification. The results are consistent with those presented in Section V, although well yield becomes a more significant predictor and other determinants of water value (precipitation and urban growth rates) are less significant.

Table 11: Benefits of Management – SWP Connections

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Ordered Logit						Logit	
	Mgt Type	Mgt Type	Mgt Type	Mgt Type	Mgt Type	Mgt Type	Mgmt	Mgmt
Avg. Well Yield	0.000579**	0.000627**			0.000733***	0.000703***	0.000687*	
	(0.000290)	(0.000290)			(0.000256)	(0.000272)	(0.000354)	
Mean Precipitation 1950-2014	0.0499	0.0271	-0.0507*	-0.0609**			0.0542	-0.0497*
	(0.0499)	(0.0558)	(0.0287)	(0.0303)			(0.0577)	(0.0301)
Well Density (Exog)	400.2	4,844***	2,273	5,987***	481.0	5,453***	638.1	3,078
	(735.6)	(1,516)	(2,196)	(1,602)	(829.0)	(1,343)	(1,043)	(3,294)
Average Urban Pop. Growth (1950-2010)	0.0243***	0.0166*	0.0198***	0.0144***			0.0485**	0.0265**
	(0.00896)	(0.00853)	(0.00599)	(0.00540)			(0.0222)	(0.0103)
Coastline Dummy	-0.820	-1.884***	-0.685	-1.218**	-0.788	-1.913***	-1.089*	-0.721*
	(0.560)	(0.613)	(0.426)	(0.476)	(0.589)	(0.635)	(0.579)	(0.399)
State Water Project Connection	1.428***	2.003***	1.690***	1.996***	1.704***	2.259***	1.206***	1.460***
	(0.388)	(0.440)	(0.313)	(0.340)	(0.356)	(0.411)	(0.392)	(0.295)
Kappa 1/Constant	1.423***	1.603***	1.098***	1.175***	1.116***	1.472***	-1.575***	-1.128***
	(0.362)	(0.377)	(0.180)	(0.196)	(0.241)	(0.270)	(0.378)	(0.185)
Kappa 2	3.677***	3.682***	3.258***	3.245***	3.212***	3.478***		
	(0.460)	(0.438)	(0.271)	(0.276)	(0.316)	(0.331)		
Observations	197	166	445	400	197	166	197	445
Missing Basins	Imputed	Dropped	Imputed	Dropped	Imputed	Dropped	Imputed	Imputed

Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1