How Transaction Costs Obstruct Collective Action: The Case of California's Groundwater

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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. Contracting 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 the transaction costs associated with contracting in explaining this variation in responses. This research adds to the literatures on open access, transaction costs, bargaining, and property rights.

Keywords: collective action; transaction costs; groundwater; common-pool resource; bargaining; 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. In this paper, we examine whether transaction costs, defined as the costs of defining and enforcing property rights (Allen, 1991, 2000), explain delayed and incomplete collective management action to address common-pool losses. Specifically, we are interested in the transaction costs that occur during an initial phase that Libecap (1993) terms "contracting for property rights." We refer broadly to *contracting costs* as those that arise during private bargaining to redefine ownership arrangements as well as efforts to define the resource's extent and characteristics.

Prior work suggests that contracting costs can prevent agreement. 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). 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. 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. While these studies suggest key factors that affect contracting costs, there have been few opportunities to empirically test the extent to which these factors impede collective action because it is difficult to define a statistically meaningful set of collective action negotiations over separate resources with varying levels of contracting costs.

This paper uses a novel, newly assembled dataset to examine factors that influence the outcome of contracting over groundwater governance regimes in California groundwater basins. The paper contributes to the literature on transaction costs by empirically examining a setting with many groundwater basins facing similar collective action problems. This approach is novel to the analysis of groundwater management, which has emerged as a crucial challenge. 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). While groundwater management districts have emerged in several states, for instance in Texas (Nachbaur, 2014) and Kansas (Edwards, 2016), and collective action is observed in groundwater management elsewhere, for instance in Kansas (Drysdale and Hendricks, 2018) and Colorado (Smith et al., 2017), California offers two advantages in examining groundwater management: (1) governance relies on a bottom-up, collective approach versus more uniform control at the state level, and (2) a relatively large number of hydrologically and economically distinct basins.

Governance institutions across California's 445 groundwater basins vary in the extent they control resource degradation. 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 these controls are likely to result in larger gains in aggregate. Basin-wide benefits rise as the resource becomes more common, as cross-well impacts become more severe, and as groundwater values rise. However, basins with high predicted contracting costs are less likely to adopt controls. Contracting costs rise with basin size, the number and heterogeneity of users, and variance in resource characteristics.

Because basin characteristics are not randomly assigned, we use prior literature on groundwater management to develop a model that explains which basins benefit from management and which will have high contracting costs. Analysis of California's groundwater basins using an ordered logit model demonstrates consistency between the factors predicted to explain management benefits and the observed choice of institutional regime. Controlling for these factors, we then examine the relationship between contracting costs and two indicators of incomplete or ineffective collective action: critically over-exploited basins that have failed to adopt property rights via court adjudication and the fragmentation of management regimes. In both cases, the presence of incomplete collective action is explained, in part, by factors that increase contracting costs.

The paper proceeds by providing background on common pool resources generally and groundwater specifically in section II. In section III we develop a stylized model to demonstrate where gains from groundwater management are likely to be high. Section IV describes our dataset, and Section V tests whether basins with higher expected benefits of management are more likely to have adopted stricter pumping controls. Section VI then examines the role of contracting costs in limiting the adoption of controls. Discussion of the importance of our results for implementing California's new Sustainable Groundwater Management Act (2014) and concluding remarks follow.

II. Background

A. Bargaining over Property Rights to a Common Pool

Institutional remedies, if employed, can 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).

Initial contracting costs rise with dispersion in users' bargaining positions, which may increase with informational problems, resource heterogeneity, and the number and heterogeneity of the bargaining parties (Libecap 1993, p. 21). Conflicting bargaining 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).

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. 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

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[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 and not warrant intervention (Gisser and Sanchez, 1980).

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.

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 it limits pumping and assigns groundwater property rights 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 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.

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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. Current elevation is not necessarily optimal economically, but for an adjudicating basin with past sustained depletion, capping pumping to maintain current levels still provides substantial benefits vs. the status quo. There exist numerous different classifications of dynamic aquifer yield (of which safe yield is one) with relevance to hydrologists and water managers (see, e.g., Pierce et al., 2013), but we restrict our discussion to the most broad and common definition applied in California's adjudication proceedings.

[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 its constituent subbasins, the number is 445, which we use here.

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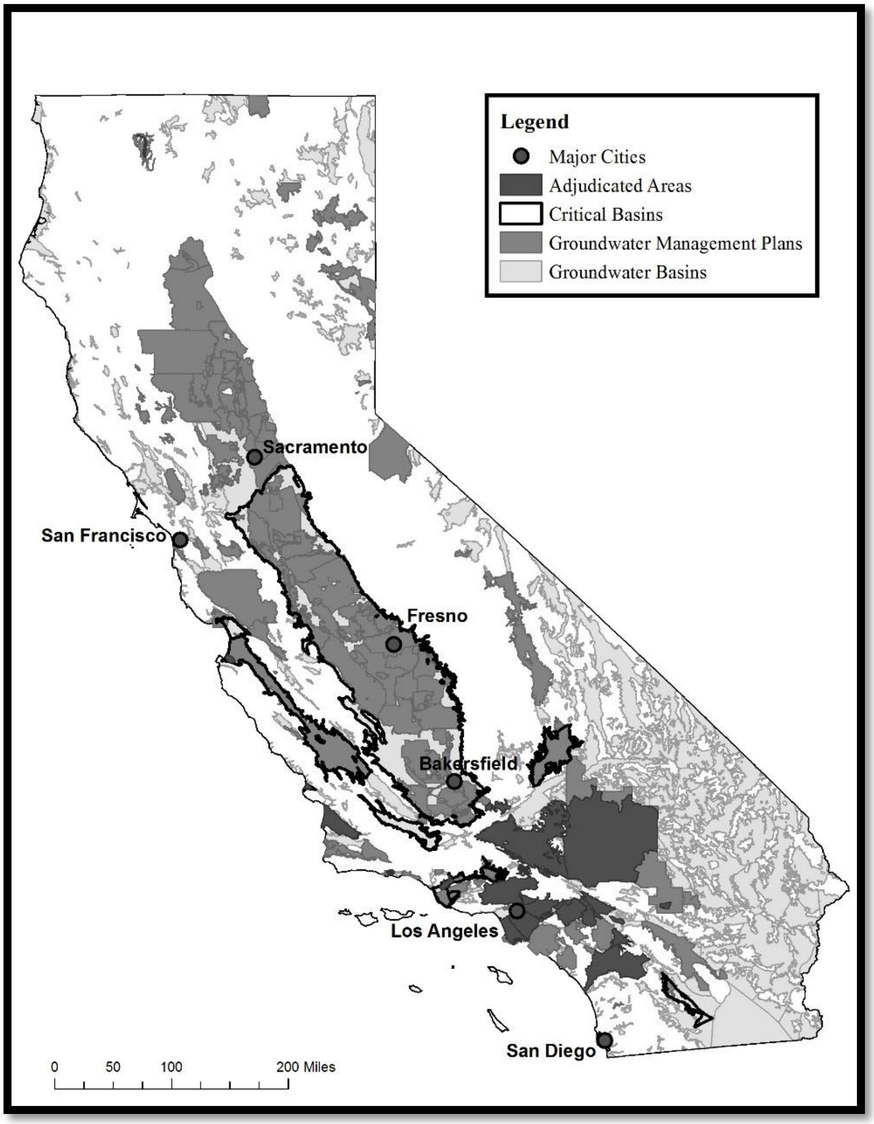
Absent adjudication or a GMP, correlative and appropriative water rights holders generally extract water without constraint, adding wells and adjusting pumping rates as individually desired.

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.

Figure 1: Locations of California's Groundwater Management Institutions



The 309 lightest-grey basins are not formally managed, and are found largely in remote areas. The 131 slightly darker polygons identify groundwater management plan areas. One hundred and five basins have multiple GMPs, covering different parts of a basin, such as the 63 GMPs above the San Joaquin Valley basin. The 25 darkest polygons designate adjudicated areas, covering 31 groundwater basins. These are primarily in more arid and urban southern California. Finally, the outlined basins are designated as critically overdrafted. Including subbasins in the central valley there are 20 critical basins in our sample. Of these, some have no governance regimes, while most have limited GMPs. These GMPs have not prevented critical overdraft.[8] The next section develops an analytic framework for understanding where groundwater management is expected to be most valuable and where contracting costs should be highest.

III. Analytic Model

In this section we present results from an economic model of groundwater extraction under two institutional arrangements: *open-access* pumping, where users pump each period until private marginal benefits equal private marginal costs; and an *optimal* pumping plan for the entire basin that maximizes aggregate rents. From the literature we identify five key externalities in groundwater pumping under open-access conditions (see Koundouri et al., 2017, and Provencher and Burt, 1993, for additional discussion): (1) the pumping cost externality associated with the increasing cost of extraction as water tables in a specific area are depleted (Brozovic et al., 2010; Peterson and Saak, 2013; Pfeiffer and Lin, 2012; Edwards, 2016); (2) a stock externality of using water too early in the transition to steady state, making less of the stock available for use later when its marginal product is higher (Provencher and Burt 1993); a

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[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.

strategic externality related to how users respond to others' pumping (Rubio & Casino, 2003; Saak and Peterson, 2007; Athanassoglou et al., 2012; Guilfoos et al., 2013); a risk externality, where pumping reduces the future ability of all users to respond to stochastic rainfall conditions (Merrill and Guilfoos, 2017); and finally an unpriced cost of pumping that exposes some users to risk of seawater intrusion (in coastal aquifers) and land subsidence (Roseta-Palma, 2002).

We develop a stylized model in steady state to compare open-access and optimal pumping plans and provide intuition into the potential gains from controls on extraction. This focuses the analysis on the pumping cost externality because the model is deterministic and strategies are limited to open-access and optimal pumping rates; the stock externality is also not modeled explicitly (see discussion in Edwards (2016) for how the results of the steady state model hold in the transition state). While this simplification does limit the model, we believe it is justified for two reasons. First, the results of the stylized model are consistent with recent literature about where gains from management will be higher (Edwards 2016; Guilfoos et al., 2013; Brozovic et al., 2010). Second, in California the key issue in aquifer management is the sustainable extraction of water from its basins. Basin adjudications and the recently implemented Sustainable Groundwater Management Act (SGMA) focus on achieving a level of pumping that will maintain average groundwater levels in perpetuity.

After modeling the potential gains from management at the basin level, we model collective action at the basin level. Basins are assumed to engage in collective action when the aggregate gains within a basin from an optimal pumping plan are high relative to the open access outcome. Gains are offset by the cost of bargaining over property rights. When negotiations involve large numbers of users or when changes to benefits and costs for individual users are not uniform, negotiation difficulty is increased. While this dispersion is caused by differences across individual pumpers, the dispersion measure at the basin level tells us about the basin-wide barriers to adoption. Importantly, this formulation as a basin-wide collective action problem is consistent with our empirical analysis, which measures all variables at a basin-level.[9]

Framework for Analyzing Aggregate Benefits of Pumping Controls

Land overlying a groundwater basin is divided into n parcels, $i = 1,2, \dots, n$. Consider the decision problems faced by any landowner overlying an aquifer: how many wells to drill, where to site them, and the rate of pumping. For simplification we assume there is a low fixed cost to drilling, so wells can exist on all potential parcels.[10] 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; costs decrease with the elevation 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:

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[9] An anonymous reviewer correctly points out that different transaction costs would likely be linked to attempts to solve each of the five externalities we discuss above. This level of detailed analysis is beyond the scope of our data, which is at the basin level. Our model is instead focused on the contracting costs that occur prior to implementation of a management program, and we leave detailed analysis of other transaction costs to later work.

[10] While wells can in reality be expensive to drill, this is a simplifying assumption in our model that allows us to ignore the decision of where to place wells by the optimal planner, who might otherwise choose to drill fewer wells to avoid the excessive capital investment that occurs under open access. In California's groundwater basins, bargaining over adopting pumping controls generally occurs after wells are drilled under an open access regime, so this assumption is likely to accurately reflect the empirical case at hand.

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

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

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

where V^M is the value of all pumping over time. The planner chooses the rate of pumping for every parcel, w_i^*, that solves this problem. The planner 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:

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

where 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.[11]

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[11] This is a simplification that holds for a fixed saturated thickness. In reality greater saturated thickness increases the cross-sectional area and the more groundwater can flow from one area of the aquifer to another, given the same hydraulic head. See Guilfoos et al. (2013) for more details.

Most groundwater basins 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:[12]

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

while the condition for optimal management is:

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

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 an optimal pumping regime. The present-value profits for any parcel i under open access 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 $\Delta = V^M - V^0$ be the gain or loss of profits in a groundwater basin with optimal relative to open access pumping.

We now use the individual gains to derive conditions for when a basin sees higher aggregate gains. Because gains from management may scale nonlinearly with the values of the

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[12] See Edwards (2016) for details.

parameters defined above, we must define a representative parameter value that captures how basin users collectively gain from adopting management. Consider a value such that if every user had their true parameter value switched to the representative parameter, while holding their other parameters at their true values, overall basin gains from management would remain constant. In other words, a user with this parameter value benefits, proportionally, just as much as the basin in aggregate from the adoption of management to address common-pool problems that depend on that parameter. We use the following notation to define the representative recharge, conductivity, distance, and profit respectively: $\bar{\mathrm{r}}$, $\bar{\mathrm{k}}$, $\bar{\mathrm{d}}$, $\bar{\pi}$. Let the basin's representative user be a hypothetical user whose individual parameters are equal to the representative parameters of the basin. Define $\overline{\Delta}$ as the gain from management of the representative user, then the following equality holds:

$$n \cdot \overline{\Delta} = V^M - V^0$$

We introduce 4 predictions regarding which basins benefit more from strict controls based on their representative user:

i. *Gains from management are increasing in conductivity: for otherwise identical basins l and j, if $\bar{\mathrm{k}}^j > \bar{\mathrm{k}}^l$, then $\Delta^j > \Delta^l$.*

ii. *Gains from management are decreasing in recharge: for otherwise identical basins j and l, if $\bar{\mathrm{r}}^j > \bar{\mathrm{r}}^l$, then $\Delta^j < \Delta^l$.*

iii. *Gains from management are increasing in well density: for otherwise identical basins j and l, if $\bar{\mathrm{d}}^j > \bar{\mathrm{d}}^l$, then $\Delta^j > \Delta^l$.*

iv. *Gains from management are increasing with the slope of the profit function: for otherwise identical basins j and l, if $\frac{\partial \bar{\pi}^j}{\partial \bar{w}^j} > \frac{\partial \bar{\pi}^l}{\partial \bar{w}^l}$, then $\Delta^j > \Delta^l$.*

All told, the characteristic basin user's benefits of strict controls increase, *ceteris paribus*, with hydraulic conductivity, aridness (lack of recharge), local well density, and the individual's marginal product of water.[13]

Framework for Analyzing the Transaction Costs of Implementing Pumping Controls

Although aggregate welfare is increased under management, users or areas on a basin may gain more or less, depending upon their characteristics and reservoir placement (Guilfoos et al., 2013). Even when there are *aggregate* net benefits from implementing management regimes that constrain individual pumping, not all parties perceive individual 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 lower-cost future resource access. In contrast, farmers prefer the flexibility of groundwater pumping and often benefit from drawdown in the near-term.

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.

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[13] The representative user is not the same as the average user; however, because we do not observe the representative user, we use mean values as a proxy in the empirical analysis. Further discussion of the validity of our empirical measures as proxies for benefits and costs is included in sections V and VI.

We posit an explicit form of contracting 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 representation of transaction costs, we add three additional predictions. In comparing two basins that are otherwise identical:

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

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

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

Prediction (v) follows because increasing the number of users will increase aggregate variance. Intuitively, it is more difficult to get larger numbers of users to agree, and coordinating the bargaining process becomes more burdensome with greater numbers of users. Prediction (vi) is clear mathematically, but requires measures of heterogeneity in pumper benefits, which we define in the next section. Prediction (vii) follows due to the correlation of basin size with factors influencing predictions (v) and (vi). Basin size raises the number of pumpers and the costs of obtaining and agreeing on reliable hydrologic information (Donohew, 2005). Larger basins will generally have more pumpers and greater disparity in pumper benefits; while larger basins are expected to have higher transaction costs, our empirical approach will not be able to separate the effect of size itself from the other contracting cost indicators, due to limited observations. In the next section we discuss how we obtained and generated the data to test these seven propositions.

IV. Data

Data on basin and user characteristics were collected for California's 445 groundwater basins, as shown in Table 1, to create a novel dataset. The borders of California's groundwater basins are defined by DWR based on hydrologic studies and local knowledge of the resource's extent. Because data is often collected using administrative boundaries as the unit of observation, rather than the resource boundaries, we convert physical, agricultural, population, economic, and well data to measures at the individual basin level. Our dataset itself represents a contribution because it provides data not previously available at the basin unit. The full details of the calculation and assumptions that went into each variable we construct are included in Appendix A.

To conduct our empirical analyses, we would like to have random assignment of basin characteristics. While this is the case with physical characteristics (barring some spatial correlation), this is not necessarily true of other measures (like population), which may depend on water management regimes. To control for endogeneity we use values of variables as they were prior to any bargaining over actions to control groundwater depletion. We do this by calculating socioeconomic variable values in either 1980 or the year prior to initiation of adjudication, circumventing any effect of groundwater management regime choice on the development of these variables.

Table 1: List of Variables

Variable	Units	Source
Measures of Management		
Adjudication of Groundwater Rights	Dummy	*Author*
Management Regime	Categorical	*DWR/Author*
Critically Overdrafted Basin	Dummy	*DWR*
Number of GMPs	Number	*DWR*
GMP Fragmentation	Ratio	*DWR/Author*
Measures of Benefits		
Well Yield	Gal/min	*DWR*
Mean Precipitation (1950 - 2014)	Millimeters (100s)	*PRISM*
Well Density	Count/Acre	*DWR/Author*
Coastline Dummy	Dummy	*DWR/Author*
Urban Pop. Growth (1950 - 2010)	Avg. Decadal Growth Rate	*CA Dept. of Fin./Author*
State Water Project Connection	Dummy	*Author*
Measures of Contracting Costs		
Agricultural/Non-Agricultural Wells	Count or Percentage	*DWR*
Well Heterogeneity	(% Ag) x (% Non-Ag)	*Author*
Number of Wells	Count (100s)	*DWR*
Basin Surface Area	Acres (1000s)	*DWR/Author*
Precip. Spatial Variance (1950 - 2014)	Millimeters (100s, squared)	*PRISM*

Mean annual precipitation and its spatial variance are constructed using 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 geographical 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. 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. These connections allow for water from the SWP (allocated through tradable entitlements) to be imported to the basin and augment its native water endowment, potentially lowering the benefits of groundwater extraction controls by expanding supply. However, such connections are typically only provided in areas with high water values that justify the investment in transfer infrastructure.

The dataset also includes the number of wells in a basin and the proportion by use category. These are calculated from well-completion reports collected by DWR. In addition, well heterogeneity is defined as $(\%\ Non - ag\ wells) \times (\%\ ag\ wells)$, which ranges from 0 to .25.

Table 2: Summary Statistics

	Adjudicated	GMP	None	Total	Critical, Unadjudicated
Number of Basins	*31*	*105*	*309*	*445*	*17*
Precipitation (mean, 100s mm)	3.1	4.5	5.3	5.0	3.0
	(1.4)	(2.8)	(4.4)	(4.0)	(1.6)
Precipitation (spat. var., 100s mm^2)	0.31	0.32	0.30	0.30	0.27
	(.38)	(.53)	(.53)	(.52)	(.42)
Basin Size (1000s acres)	182	179	49	89	493
	(256)	(441)	(113)	(250)	(462)
Coastline Dummy	0.19	0.10	0.15	0.14	0.12
	(0.40)	(0.29)	(0.35)	(0.34)	(.33)
Well Yield Avg (gallons/min)	709	749	425	562	1,185
	(490)	(600)	(559)	(584)	(406)
Number of Wells (Count)	604.2	836.3	56.6	278.8	2,112.9
	(1,057.1)	(3,178.8)	(333.4)	(1,623.2)	(3,561.0)
Well Density (Count/acre)	0.00236	0.00517	0.00247	0.00310	0.00489
	(0.00220)	(0.00856)	(0.00535)	(0.00622)	(0.00486)
Well Heterogeneity	0.1527	0.1208	0.0561	0.0781	0.2039
	(0.0783)	(0.0993)	(0.0886)	(0.0965)	(0.0611)
Urban Population Growth (%)	25.58	16.41	3.76	8.26	32.75
	(39.81)	(25.54)	(15.46)	(21.82)	(13.91)
SWP Connection	0.77	0.29	0.10	0.19	0.35
	(0.43)	(0.45)	(0.30)	(0.40)	(0.49)

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. Using these measures of the stringency of pumping constraints, the next section links the level of constraint to the benefits basins can potentially receive from implementation. Table 2 provides summary statistics by management stringency, as well as for those basins that are critically overdrafted yet not managed. The table shows that, generally, the conditional means of variables predicted to increase the benefits of management are higher for areas with more stringent adjudications; we test this more rigorously in section V. It is also generally true that the conditional means of transaction cost variables in the critical, unadjudicated basins are higher than in the adjudicated basins; we test this more rigorously in section VI.

V. Benefits of Pumping Constraints and Collective Action

A. Empirical Strategy

In this section we examine predictions (i)-(iv) by looking at whether the observed adoption of pumping controls is consistent with our predictions of where basin benefits of pumping are predicted to be higher. 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 $\hat{\kappa}_1, \hat{\kappa}_2, \hat{\beta}_1, \hat{\beta}_2, \dots, \hat{\beta}_n$ 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 estimate the effect of well yield (a proxy for hydraulic conductivity), precipitation, well density, and urban growth (a proxy for where water value is higher) on the latent benefits of pumping controls via an ordered logit regression. In reality, the interaction among these variables and optimal pumping is more complex than is represented in our analytic model.[14] We evaluate whether the model's predictions, presented in Table 3, are consistent with empirical observations

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[14] Well yield is generally influenced by hydraulic conductivity, saturated thickness, and well depth in unconfined aquifers. It is possible that as a proxy for hydraulic conductivity, well yield may be influenced by unobserved differences in saturated aquifer thickness and well depth. While it may be that users drill deeper wells where water is more valuable, we include several proxies for water value and our results are consistent. Furthermore, data on well depths show that average depths do not vary significantly by management regime, and including average depth in our ordered logit does not affect results. Additionally, hydraulic conductivity in general varies by orders of magnitude more than saturated thickness (Dunne and Leopold, 1978; Domenico and Schwarz, 1990) and evidence from California suggests this relationship holds within the state, indicating that variation in well yields is driven by variation in hydraulic conductivity. More details on well yield as a constraint to irrigated agricultural production can be found in Collie (2015) and Foster et al. (2015). Where low conductivity causes well-yield constraints on the rate of extraction, open-access outcomes should deviate less from the social optimum because users can only pump water in their immediate vicinity, in essence creating a "wall" around their resource. In contrast, where yields are high, pumpers can more readily pull water from neighbors, increasing the common resource problem.

for a variety of variable combinations and models. In some specifications, we include the State Water Project connection variable. The variable may potentially lower the benefits of groundwater extraction controls by making water more readily available, but is also highly correlated with water value (and urban population growth). Accordingly, the predicted sign of the variable is ambiguous. Finally, although it is not one of our predictions, there is significant discussion in California of the importance of seawater intrusion as a driver of management, and for this reason we include a coastline indicator.

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

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

We do not include measures of contracting costs in our primary ordered logit regressions because we are interested in producing a measure of aggregate basin benefits that we can leverage in Section VI to assess the validity of a counterfactual comparison; however, there is also reason to believe that the ordered logit is not well-suited to test the impact of these cost variables on the likelihood of adopting management. Larger basins, those with more users, and those with high proportions of urban users tend to have valuable water, and moreover these characteristics are correlated with the existence of any common-pool problem. In basins with few wells and little stress on the resource, contracting costs are low, as are aggregate benefits. As a result, cost variables will be correlated with management without a clear causal mechanism. In Appendix D we include the cost variables in the ordered logit analysis and provide evidence that the benefit variables explain the adoption of management, even when transaction cost variables are included.

Table 4: Basin Benefits of Management

	(1)	(2)	(3)	(4)	(5)	(6)
		Ordered Logit			Logit	
	Mgt Type	Mgt Type	Mgt Type	Mgmt	Mgmt	Mgmt
Avg. Well Yield	0.000482*		0.000550*	0.000659*		0.000698**
	(0.000290)		(0.000284)	(0.000354)		(0.000344)
Mean Precipitation 1950-2014	-0.0543	-0.116***	-0.00707	-0.0712	-0.112***	-0.0321
	(0.0542)	(0.0312)	(0.0557)	(0.0623)	(0.0327)	(0.0633)
Well Density (Exog)	46.52***	46.43***	44.23***	100.9***	59.60**	95.00***
	(14.39)	(15.23)	(14.18)	(33.46)	(25.63)	(35.23)
Average Urban Pop. Growth (1950-2010)	0.0308***	0.0266***	0.0231***	0.0486***	0.0299***	0.0432**
	(0.00779)	(0.00554)	(0.00841)	(0.0188)	(0.00910)	(0.0200)
Coastline Dummy	-0.291	-0.121	-0.646	-0.877*	-0.280	-1.129**
	(0.428)	(0.349)	(0.516)	(0.476)	(0.345)	(0.526)
State Water Project Connection			1.313***			1.052***
			(0.373)			(0.376)
Kappa 1/Constant	0.839**	0.672***	1.316***	-1.057***	-0.723***	-1.466***
	(0.347)	(0.170)	(0.363)	(0.358)	(0.173)	(0.374)
Kappa 2	2.969***	2.662***	3.576***			
	(0.473)	(0.278)	(0.457)			
Observations	197	445	197	197	445	197

Notes: Robust standard errors in parentheses with significance levels: *** p<0.01, ** p<0.05, * p<0.1. The number of observations is determined as follows: The entire data set is 445 observations. If well yield is included, the dataset collapses to 197 observations due to missing values.

Table 4 presents results using only measures of aggregate benefits, where contracting costs are represented as average values in the estimated Kappa cutoff coefficients. Most specifications include the conductivity measure, well yield, which is available only for 197 basins. Columns 1-3 report estimates for an ordered logit across the three types of management, while columns 4-6 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.[15] Columns 1 and 4 reflect baseline specifications that include all

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[15] 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

variables with clear management benefit predictions, and columns 3 and 6 include a dummy variable for state water project connections.[16]

Across all specifications, the findings are broadly consistent with model predictions (i)-(iv) in Section III.[17] Well yield is positive and statistically significant at the 10% or higher level in all 4 specifications, and both urban population growth (as a proxy for value) and well density are highly significant in all specifications. Precipitation has negative effects in all specifications, while its significance and magnitude depends on whether the full sample, which has more variation in precipitation, is used. State Water Project connections seemingly proxy for water value as well, with estimated coefficients that are large, positive, and statistically significant. The results are robust to its inclusion.[18]

Table 5 presents estimates of the marginal effects of the results shown in Table 4, column (1). 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 falling into the adjudicated category by 5.48 percentage points and of adopting a GMP by 12.09 percentage points. The effects of well yield and density are of slightly smaller magnitude. The underlying probability of adjudicating groundwater rights is around 8% and of having a GMP

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assessed using a Brant Test. Although we find evidence that this assumption can be rejected (the coefficient estimates moving from unmanaged to GMP are not necessarily the same as moving from GMP to adjudicated), the point estimates and significance levels from the ordered logit are generally consistent to those in a simplified logit estimation.

[16] In all columns the San Joaquin Valley groundwater basin is broken into its constituent sub-basins as defined by DWR, although it is generally considered a single hydrologic unit. We agglomerate the San Joaquin subbasins into one basin and present the results in Appendix B).

[17] As a robustness check, other regression specifications including our SWP variable are included (Appendix C). The results remain broadly consistent with those reported here. We also test the predictive power of this model and find that, on average across specifications, the ordered logit places basins into the correct category 68% of the time, and the logit model 62%.

[18] The estimated coefficient on the coastline dummy is consistently negative. 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. Results are robust to its removal from the regressions.

around 34%. 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	-6.88%	-7.80%	-17.57%
GMP	4.78%	5.41%	12.09%
Adj.	2.11%	2.39%	5.48%

Observationally, the variables 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 (562), and high well densities.[19]

High expected aggregate benefits alone, however, may *not* 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 had not agreed upon pumping restrictions until very recently despite earlier attempts. Accordingly, we turn now to examining the determinants of contracting costs that impede collective action.

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[19] 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).

VI. Contracting Costs as Impediments to Collective Action

A. Empirical Strategy

We do not observe contracting costs directly and have modeled these costs as increasing in the number of users, heterogeneity in their payoffs, and basin size. While we observe the number of users and basin size directly, heterogeneity in benefits is less readily observable. We use two measures of heterogeneity: heterogeneity in well type and in spatial heterogeneity of precipitation. We measure the effect of our proxies for contracting costs in molding group responses to open-access losses in two 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 contracting 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. To do so requires the identifying assumption that, absent transaction costs, critical and adjudicated basins are similar. We support this assumption by examining how these two sets of basins differ across observable determinants of benefits.

Second, 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. Fragmented GMPs represent an incomplete solution to groundwater drawdown and are thus always a second-best solution. 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. This analysis requires that basins with higher benefits do not have lower fragmentation, per se. Although the level of benefits across these basins certainly varies, statistical tests suggest the fragmentation of GMPs is actually higher in basin with higher predicted benefits, although the association is not statistically significant.

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.[20] 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 (23 adjudicated, 16 critical) for this comparison. We predict a management benefits value using average well yield, well density, average precipitation, a coastline dummy, the average decadal urban population growth rate from 1950 to 2010, and SWP connection (column 3, Table 4). We then estimate a probit regression of adjudicated status on modeled benefits to ascertain whether benefits vary systemically across groups. The results are shown in specification (1) of Table 6.

Our average index of the benefits of adopting pumping constraints is not statistically different between the two groups, which reinforces the relevance of this empirical test: if the benefits of curtailing excessive pumping are as high in these critical basins as in other adjudicated basins, why have they not also adjudicated property rights? To assess the impact of transaction cost variables, we turn to predictions (v)-(vii) from Section III regarding the effect of

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[20] A detailed definition of critical overdraft can be found here: http://www.water.ca.gov/groundwater/sgm/cod.cfm. Most basins defined as critically overdrafted have been in this state for decades, although designation by California's DWR only occurred in 2015. For example, water table elevations have been dropping precipitously in California's central valley since at least the 1960s, with few periods of recovery due to above-average precipitation. The Santa Clara Valley and downstream Oxnard Plain have experienced high extraction rates and seawater intrusion since the 1980s. To our knowledge, in none of the critical basins have acute problems emerged recently.

basin size, the number of users, and heterogeneity in pumpers and the resource. We estimate the same probit regressions for each transaction cost variable and predict that these variables systematically reduce the likelihood of defining property rights. The results are shown in columns 2-7, Table 6.

Table 6: Effect of Contracting Costs on Likelihood of Adjudication

Probit (Adjudicated)	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Predicted Benefits	0.00371 (0.187)						
Log Basin Area (acres)		-0.321** (0.153)					-0.0106 (0.311)
Log Number of Wells (Exog)			-0.32*** (0.0922)				-0.269 (0.224)
Well Heterogeneity (Exog)				-6.527** (3.276)			-4.466 (3.559)
Mean Spatial Precip. Variance 1950-2014					0.141 (0.520)		
SWP Connection						1.124*** (0.402)	
Constant	0.219 (0.430)	4.151** (1.860)	2.179*** (0.555)	1.542** (0.651)	0.333 (0.238)	-0.282 (0.303)	2.820 (2.810)
N	39	48	48	48	48	48	48

Standard errors corrected for heteroscedasticity, and significance as follows: *** p<0.01, ** p<0.05, * p<0.1.

As predicted, larger basins with more wells and more heterogeneous users are less likely to adopt management, benefits being equal. The managed basins are more likely to have imported water connections, which is consistent with the notion that imported water lowers the costs of adjudication.[21] Specification (7) presents the results using three contracting cost variables simultaneously. The coefficient estimates in the simultaneous estimation have the correct signs, although the low number of observations leads to large standard errors. A Wald test, however, indicates the coefficients are jointly significant, and subsequent model

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[21] 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 to recharge rather than restricting pumping. Where the costs of reductions are very high, this may be more efficient and ease agreement.

specification tests suggest that basin size and well heterogeneity are important model components, with the number of wells less so. This regression provides context for the results on the variables individually: while measures of contracting costs are higher in critical basins, our small number of observations limits our ability to determine the relative importance of the variables comparatively.

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 0.16, much higher than the sample average of 0.07.

C. *Fragmentation of Groundwater Management Plans*

In the absence of transaction costs, one GMP with complete coverage of a basin could address all user concerns. When parties cannot agree on basin-wide groundwater management, partial plans covering only portions of the basin may emerge to encompass smaller, more homogeneous groups 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 entirety and thereby reflects how difficult it is for users to collectively realize gains from management. Using all groundwater basins with GMPs, we estimate $Y_i = X_i'\beta + u_i$, with log GMP fragmentation as the dependent variable. The results are reported in Table 7.

Table 7: GMP Fragmentation and Bargaining Costs

Log GMP Fragmentation	(1)	(2)	(3)	(4)	(5)	(6)
Log Basin Area (acres)	0.206***					0.196***
	(0.0315)					(0.0438)
Log Number of Wells (Exog)		0.143***				-0.00999
		(0.0259)				(0.0448)
Well Heterogeneity (Exog)			2.072***			0.806
			(0.704)			(0.933)
Mean Spatial Precip. Variance 1950-2014				0.316**		0.263**
				(0.155)		(0.124)
Coastline Dummy					-0.00033	-0.0251
					(0.200)	(0.174)
Constant	-0.0729	0.0781	0.424***	0.578***	0.681***	-0.175
	(0.111)	(0.115)	(0.103)	(0.0688)	(0.0735)	(0.112)
N	122	122	122	122	122	122

Standard errors in parentheses and corrected for heteroscedasticity and spatial autocorrelation, and significance as follows: *** p<0.01, ** p<0.05, * p<0.1.

Coefficients for basin size, the number of users, user heterogeneity, and mean spatial precipitation variance (recharge differences) are positive and significant in specifications 1-4. While the small number of observations limits statistical power, basin area and recharge variance remain significant in specification 6. The table suggests that GMP fragmentation is more likely to occur in larger basins with pumpers who differ in water valuation and where recharge varies.

D. *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 may limit agreement on what remedies are adopted: 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. These costs are not trivial: contentious litigation processes in some basins have resulted in total costs likely exceeding $11 million (Cal Coast News, 2013), and expert opinion suggests other basin adjudication processes have sometimes been significantly more expensive (McGlothlin, 2016). Indeed, recent work (Ayres and Meng, 2018) calculates a lower bound for the benefits of basin adjudication in the Mojave of over $60 million—a case where agreement nonetheless took two attempts over forty years to achieve. In particular, users in California's critical basins encounter especially high costs in curtailing excessive exploitation. These basins are on average larger with a larger number of differentiated users than is the case in basins where parties have successfully agreed upon an allocation of property rights. Because we are comparing two sets of otherwise similar basins, this result is compelling. However, redefining explicit legal rights to groundwater is not the only measure available to basin users wishing to address common-pool problems; for example, problems of cross-well interference and seawater intrusion can sometimes be addressed with less restrictive rules. So, we examine the groundwater management plans as well and find that fragmentation of management plans also is more likely as basin size increases, as water values differ more greatly, and as variance in recharge increases.

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 drinking-water users (urban utilities) 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)).

California has recently undertaken steps to increase the number of basins with adjudication-like management outcomes through the Sustainable Groundwater Management Act (2014). The legislation requires that basin users form Groundwater Sustainability Agencies (GSAs) in order to draft and submit sustainability plans to state regulators. In the summer of 2017, GSA formation documents were submitted, and fragmentation in GSA coverage mirrored in many cases that of existing GMPs, suggesting that contracting costs remain important barriers to improved management.

If basin users and state regulators wish to implement the act and transition to new management regimes efficiently, they will need to work to make either up-front collaboration or *ex post* contracting among GSAs smooth by lowering contracting costs. How can this be achieved? The state has already made professional facilitators available to interested parties, which may lower costs of negotiation.[22] Because each institutional remedy requires agreement on different rules, the state should also remain open to management approaches that economize on contracting costs by addressing relevant issues within a basin without going so far as to define pumping allocations or include all potential actors; in the past, basin users have adopted spatially restricted management rules to address seawater intrusion, written contracts to share imported water in order to avoid costly production restrictions, or adopted well-spacing restrictions to address cross-well interference without restricting pumping rates. Such finely tailored responses may not explicitly meet all of the targets set forth in SGMA's enabling legislation, but they may be sufficient to address user concerns while avoiding points of contentious disagreement. Finally, in cases where explicit volumetric rights must be defined, certain allocation schemes may lend themselves more readily to agreement; for example, anecdotal evidence suggests that in basins where soil quality is homogeneous and crop diversity is low, allocation based on irrigated acreage is preferred to grandfathering based on previous pumping rates, which are difficult to measure and verify. Such considerations will prove important in crafting strategies to reach agreement and address persistent or emerging basin concerns.

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[22] https://www.water.ca.gov/Programs/Groundwater-Management/Assistance-and-Engagement

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 contracting to reach 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 contracting 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 others and hence push for early and more complete action. Others feel less imperative, particularly if the response offers them less than 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 contracting 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 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 provides data for investigating the sources and impact of transaction costs. While the 445 groundwater basins do not represent a randomized experiment, the preponderance of evidence from our analysis offers a clear explanation for 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 contracting 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.[23] 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.

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 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

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[23] https://gis.water.ca.gov/app/gicima/

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.

Urban Population Growth

Historical census data for major municipalities were obtained from the California Department of Finance[24] 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.[25]

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.

SWP Connections

Water agencies and irrigation districts holding *Table A* allotments from the State Water Project[26] were identified, and GIS shapefiles of water agencies in California[27] 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.

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[24] http://www.dof.ca.gov/Reports/Demographic_Reports/index.html#reports
[25] http://52.26.186.219/internships/useit/content/california-cities-point-shapefile
[26] http://water.ca.gov/swpao/swp-max-table-a.html
[27] https://gis.water.ca.gov/app/gicima/

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.

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.

B. Results with San Joaquin presented as one Basin

In this subsection we present the results of our ordered logit and logit models 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 8: Benefits of Management – San Joaquin Whole

	(1)	(2)	(3)	(4)	(5)	(6)
		Ordered Logit			Logit	
	Mgt Type	Mgt Type	Mgt Type	Mgmt	Mgmt	Mgmt
Avg. Well Yield	0.000518*		0.000548*	0.000625*		0.000661**
	(0.000312)		(0.000292)	(0.000338)		(0.000324)
Mean Precipitation 1950-2014	-0.0506	-0.112***	0.000484	-0.0683	-0.107***	-0.0248
	(0.0531)	(0.0305)	(0.0551)	(0.0618)	(0.0319)	(0.0633)
Well Density (Exog)	43.98***	44.71***	40.63***	97.69***	58.06**	91.40***
	(14.08)	(14.43)	(13.64)	(32.54)	(23.80)	(34.67)
Average Urban Pop. Growth (1950-2010)	0.0298***	0.0233***	0.0208**	0.0394**	0.0226***	0.0325
	(0.00858)	(0.00579)	(0.00920)	(0.0187)	(0.00769)	(0.0204)
Coastline Dummy	-0.311	-0.0100	-0.759	-0.558	-0.0429	-0.881*
	(0.391)	(0.322)	(0.508)	(0.449)	(0.317)	(0.524)
State Water Project Connection			1.428***			1.122***
			(0.412)			(0.385)
Kappa 1/Constant	0.892**	0.727***	1.386***	-1.070***	-0.781***	-1.499***
	(0.346)	(0.172)	(0.359)	(0.354)	(0.173)	(0.373)
Kappa 2	2.705***	2.511***	3.335***			
	(0.441)	(0.260)	(0.426)			
Observations	185	430	185	185	430	185

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

C. Benefits Results with State Water Project Connections

Here 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 9: 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 and significance as follows: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

D. Benefits Results with Transaction Cost Variables

In Table 10 we present ordered logit results including all variables that we believe are tied to transaction costs.

Table 10: Benefits of Management – Tests with Contracting Costs

	(1) Mgt Type	(2) Mgt Type	(3) Mgt Type	(4) Mgt Type	(5) Mgt Type	(6) Mgt Type
Avg. Well Yield	0.000039	0.000178	0.000029	0.000183	0.000091	0.000190
	(0.000314)	(0.000311)	(0.000468)	(0.000443)	(0.000471)	(0.000453)
Mean Precipitation 1950-2014	-0.0538	-0.00166	-0.193**	-0.124	-0.205**	-0.125
	(0.0645)	(0.0657)	(0.0893)	(0.0855)	(0.0922)	(0.0873)
Well Density (Exog)	9.762	5.478	19.13	11.23	17.91	18.20
	(18.10)	(20.48)	(21.51)	(27.89)	(22.74)	(26.78)
Average Urban Pop. Growth (1950-2010)	0.0101	0.00274	0.0213**	0.0128	0.0232***	0.0145
	(0.00750)	(0.00794)	(0.00859)	(0.00942)	(0.00815)	(0.00885)
Coastline Dummy	-0.105	-0.452	0.443	0.280	0.402	0.267
	(0.451)	(0.532)	(0.569)	(0.679)	(0.580)	(0.680)
Log Number of Wells (Exog)	0.443***	0.477***	0.0163	0.0765		
	(0.112)	(0.115)	(0.165)	(0.158)		
Log Basin Size					-0.0678	0.0345
					(0.156)	(0.160)
Well Heterogeneity (Exog)	0.536	-1.220	-0.487	-2.678	-0.322	-2.458
	(2.089)	(2.159)	(2.975)	(2.947)	(2.909)	(2.876)
Mean Spatial Precip. Variance 1950-2014	-0.280	-0.303	-0.124	-0.274	-0.0535	-0.227
	(0.321)	(0.320)	(0.384)	(0.372)	(0.378)	(0.367)
State Water Project Connection		1.327***		1.438***		1.428***
		(0.396)		(0.491)		(0.491)
Kappa 1	1.884***	2.336***	-1.047	-0.497	-1.353	-0.633
	(0.393)	(0.421)	(1.036)	(0.978)	(1.067)	(1.019)
Kappa 2	4.182***	4.770***	1.319	2.088**	1.012	1.947*
	(0.522)	(0.515)	(1.097)	(1.013)	(1.123)	(1.056)
Observations	197	197	104	104	104	104
Sample	Full	Full	Restricted	Restricted	Restricted	Restricted

Robust standard errors in parentheses and significance as follows: *** p<0.01, ** p<0.05, * p<0.1.

We find that coefficient estimates for variables in our original specification have the same signs and are generally robust, although some lose significance. Furthermore, estimated coefficients for (log) number of wells are positive using the full sample (columns 1 and 2), which is unsurprising: basins with few wells do not suffer from large common-pool losses and are thus unlikely to adopt management. Because many basins have few users and thus low gains from adopting pumping restrictions, including our contracting cost variables that are correlated with water value and basin benefits does not result in a clean empirical test of their role. Therefore we restrict our sample by dropping basins that have fewer than 50 wells and are considered to be "low priority" for management by DWR. Such prioritization was undertaken as part of the California Statewide Groundwater Elevation Monitoring (CASGEM) effort and is based on estimates of current extraction, recharge, overlying population, etc. This results in a sample of 142 basins (104 of which have well yield data). Columns 3-6 present results for this sample with either log number of wells or log basin size, and SWP connections in alternating columns. We find again that our original estimates for variables that determine benefits are robust in sign, although a lower number of observations increases standard errors. Furthermore, we find that coefficients on contracting cost variables now tend to be negative in sign, corroborating our narrative that the full sample includes low-value basins that caused the coefficient on number of wells to appear strongly positive due to its correlation with the existence of a common-pool problem at all. Although we find that the contracting cost variables are generally associated with a lower likelihood of adopting management, we refer the reader to Section VI, where we present a much cleaner econometric test of the role of the number of users and user and resource heterogeneity in inhibiting the formulation of pumping restrictions.