Choosing Remedies for the Common Pool: The Case of California's Groundwater Management

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March 4, 2016

Abstract:

In the absence of some form of regulatory control, common-pool resources (CPRs) are subject to over-extraction and rent dissipation. Where losses are large, strengthening institutional controls such as property rights can be welfare improving. Economic theory supports the notion that institutions to address common-pool problems emerge when their benefits exceed costs. Although there is a substantial literature examining why property rights and other institutional controls emerge, they are often focused on a single CPR, and there are relatively few broad empirical tests. This paper examines the institutions governing 430 groundwater basins in California to determine whether the theoretical determinants of benefits and costs predict more stringent institutional control. Consistent with our propositions, basins are more likely to adopt strong property right institutions via court adjudication where benefits are high and costs are low, relative to non-adopting basins. Groundwater management plans are shown to be an intermediate option for controlling over-extraction, emerging in basins where benefits are lower than adjudicated basins, but higher than non-adopting basins.

JEL Codes: P48, K11, Q15, Q25, Q58

I. Introduction

Common-pool resources (CPRs) are characterized by low excludability and high rivalry. Examples include many natural resources, such as common fish or timber stocks. Limiting CPR use is expensive, and potentially technically infeasible, and resource rents may be dissipated because the resource is subtractable (Ostrom, 1994: p. 4). Under open access conditions, common-pool rent dissipation may be quite costly, but institutional remedies can mitigate these losses. Economic theory predicts that institutions increasing excludability, such as property rights, will be adopted when benefits exceed costs (Demsetz, 1967). Because the legal process of assigning rights is expensive, as is the monitoring and enforcement of those rights after their creation, the efficient level of institutional control will be such that marginal costs and benefits are equalized (Anderson and Hill, 1975).

Although there is much discussion of when property rights will be strengthened to limit open-access problems, there are relatively few empirical tests. Management of groundwater offers an interesting opportunity due to heterogeneity in the level of open-access rent dissipation among otherwise similar basins. In California, aquifers vary along several dimensions, as do the users who rely on their water, and these characteristics are key determinants of the extent of common-pool losses. The legal process of assigning rights is expensive, as is the monitoring and enforcement of those rights after their creation – only 24 adjudications have been undertaken, covering 32 groundwater basins out of 430. Therefore, we test the general proposition that basins where the common-pool losses are greatest relative to these costs are most likely to undertake action to limit over-extraction. Data on aquifer, geographic, and demographic characteristics of California's 430 groundwater basins are used to statistically examine the factors that create benefits for basins to undertake management and the costs that limit the adoption of more complete property right institutions.

Specifically, we examine the adoption of two institutional remedies available to users of groundwater in California: groundwater management districts and basin adjudication. Adjudication is a well-established legal procedure in which groundwater pumpers come before a state court in order to change the legal definition of their pumping rights, often creating secure, tradable permits to pump a share of a capped aggregate volume of water. Groundwater management districts represent a cheaper but less comprehensive form of control over groundwater pumping introduced by state legislation in 1992. We demonstrate, consistent with our propositions, that basins are more likely to adopt strong property rights institutions where benefits are high, relative to non-adopting basins. Groundwater management districts are shown to be an intermediate option for controlling over-extraction, emerging in basins whose benefits are lower than adjudicated basins, but with higher benefits than non-adopting basins.

The paper begins with background on groundwater in California and then develops a conceptual model. Building upon the results of the model, an empirical strategy is presented and the results are analyzed. Concluding remarks follow.

II. Background

Common-pool Problems

That common-pool resources may be subject to substantial or complete rent depletion[1] under conditions of individual competition has been recognized for some time (Gordon, 1954; Hardin, 1968). Others have argued that the fundamental problem is related to the definition of economic property rights to the resource (Coase, 1960). When property rights are assigned through capture, i.e., only upon capture or use of the resource, incentives for resource maintenance and efficient use are not present. A canonical example is that of an unregulated fishery: when property rights are not well defined, a race to fish may result that depletes fish stocks to the point that aggregate resource rents are extinguished – the cost of catching any remaining fish equals their value. Although the problem has often been studied from the perspective of unregulated fisheries, the dynamics are more general. Groundwater aquifers represent another case in which resource rents are compromised under open-access regulatory conditions.

New institutions may emerge to address these common pool resource losses. In Kansas, for example, groundwater management districts emerged in the early 1970s to address growing local depletion problems (Edwards, 2015). In Nebraska, new groundwater right markets have emerged to address surface-groundwater issues (Kuwayama and Brozovic, 2013). In a simple theoretical sense, these institutions will be adopted when the benefits to be gained from their formulation exceed any additional costs of monitoring and enforcement that they may require – as the value of water increases or common-pool losses become more acute, more secure property rights institutions may be introduced (Demsetz, 1967). These new institutions, designed to address the inefficient resource use that results from their absence, could in practice take the form of social norms, informal rules, or more formal, codified rules (Ostrom, 1990). In many cases, resource users find themselves in the position of formulating legal property rights in order to more concretely define economic property rights, which determine who the residual claimants to the resource are (see Barzel, 1987).

However, the adoption of new institutions is not simply a matter of aggregate net gains to be had from more clearly defining who has rights to access the resource and to what extent. Any institutional change, whether it is from an open access regime to the definition of legal property rights or something as subtle as changes to rules about what technologies or tools may be used to access the resource, can make some resource users better off and others worse off. As a result, the formulation of institutions to address what may seem to be an obvious common-pool problem takes on a political character as potential winners and losers bargain over their adoption. As Libecap (1989) notes, "[t]he stands taken by influential parties and the concessions made to reach political agreement on the allocation and definition of rights critically fashion the institutions that are adopted at any time." These bargaining positions are determined by the status quo or existing institutional regime as well as from the physical and economic characteristics of the resource and its users. Indeed, even in cases where aggregate net benefits of a new regime may be large, some users may rationally oppose the transition (Costello and Grainger, 2015) and the costs of bargaining to bring them on board may be prohibitive (Johnson and Libecap, 1982). In the case of contemporary groundwater management in California, the shift away from adherence to the correlative rights doctrine requires exactly this kind of bargaining amongst resource users.

Groundwater as a Common-pool Resource

Groundwater is a textbook example of a common-pool resource; agents share a finite – yet renewable – amount of water, and each person's use affects the resource stock and the level of water in the aquifer. Under open access, pumpers extract groundwater until the marginal private costs of doing so equal the marginal benefits. These private costs include the costs of pumping as well as the private

[1] Here we mean by "rent depletion" that the total economic value of the resource can be lessened or exhausted through over-extraction or the expenditure of excessive effort to capture the resource.

portions of the scarcity value of water, local drawdown effects, and any collateral effects of declining water levels (e.g., seawater intrusion or subsidence).

However, the socially optimal rate of pumping is characterized by each user extracting to the point that marginal private benefits are equal to the aggregate social cost incurred by his/her pumping. These include the full scarcity value of the water in the future, the sum of all pumpers' increased pumping costs due to water level decline as well as local drawdown effects, and the sum of all social costs of collateral impacts of declining groundwater levels. These costs will vary based on the location of the pumper, both in absolute and relative terms: pumpers in areas where groundwater naturally flows towards others will have a larger impact on water levels elsewhere, pumpers closer to the coastline may cause a greater risk of seawater intrusion, and pumpers located in areas of dense well spacing cause larger spatial externalities.

An open-access regulatory framework thus results in a potentially large wedge between each pumper's rate of extraction and what would be socially optimally. In aggregate, this can lead to substantial dissipation of the resource's rents.

Open Access in California

In California, groundwater extraction is generally governed by the correlative rights doctrine, where all landowners overlying an aquifer may pump water as needed.[2] In addition, appropriative water users are those who have been granted rights to pump water for use on lands other than those owned by the rights holders.[3] The vast majority of rights holders are overlying rights holders. Both of these rights are subject to beneficial and reasonable use rules, which have often been interpreted to include a large set of relatively low-value uses, such as irrigating low-value crops. As such, although the current institutional framework restricts the number of users, it doesn't effectively cap aggregate pumping volumes. Especially during drought, groundwater is used as a buffer supply and periods of significant drawdown of water levels result.

Thus, the correlative rights doctrine offers one solution to common-pool problems in groundwater basins by limiting the extraction of groundwater to a finite group of pumpers, but it still retains fundamental open-access characteristics. Of primary importance is that, since property rights to the resource and all of the services it provides are not well defined, pumpers have an incentive to extract without regard to the effects of their pumping on others.

The effects of open-access groundwater management in California are difficult to assess directly, but many indications of resource degradation and excessive pumping exist. Over the past several decades, stored groundwater has declined substantially in California's Central Valley (Famiglietti et al., 2011), primarily as a result of agricultural pumping during droughts, when surface water is less available. Other indicators of resource degradation include surface level subsidence and seawater intrusion. Subsidence has been a major problem in California's Central Valley as well as elsewhere in the state: from 2006-2010, some areas saw land elevations drop 6-24 inches (Farr et al., 2015). Meanwhile, concerns over

[2] In principle, should groundwater resources prove insufficient to meet the needs of all correlative rights holders, all users would share equally in any cutbacks. However, it is possible for users to establish larger rights (allocations) by prescription, i.e., through open and notorious use of the resource that infringes on another agent's rights. One result of this is that adjudications often base allocations on historical use and those who did not pump in the past lose their rights by prescription. Mutual prescription as a benchmark for adjudicating water rights was recognized in the Raymond Basin adjudication (1944).

[3] A ubiquitous example is a water utility that has rights to pump groundwater but then distributes this water to ratepayers throughout its service area.

seawater intrusion have been present in the Los Angeles basin since the 1950s and have also prompted several recent court adjudications in Seaside and the Santa Maria Valley.

Groundwater Remedies in California

Options for institutional control of groundwater in California include (1) groundwater basin adjudication to further define rights; (2) the formulation of groundwater management plans under existing legislation, which may not restrict pumping; and (3) the de facto rules of the correlative rights system.[4]

The initial legal precedents for adjudicating groundwater basins in California were set in the 1940s and 1950s, when Raymond Basin and the Upper LA River Basin adjudicated. In the adjudication process, those agents holding rights to pump groundwater come before a State Court in order to change the legal definition of those rights. This may entail simply defining an annual safe yield for the basin, more clearly delineating who has the right to pump, or, in many cases, quantifying how much each user is entitled to pump annually. Because appropriative rights to groundwater are often assigned to other water users within a basin, adjudication typically involves grandfathering the rights of overlying and appropriative users. In many cases, a watermaster, a third-party entity, is identified by the court to enforce the new system of economic property rights.[5]

After adjudication is completed, the maintenance of the safe yield of the basin is expected to improve the health of the aquifer, reduce pumping costs as external costs of pumping are more adequately addressed, and reduce the risk of seawater intrusion in coastal areas. Some adjudications have proven more successful than others: for example, rights were quantified in the Central Basin and hydrographs show recovering groundwater levels, while the Santa Margarita adjudication has failed to quantify groundwater rights and signs of sustained overdraft remain. In many cases, rights to pump groundwater are quantified and these rights become transferable, which allows for gains from trade to be realized. Although many basins do not experience much trading, leases and permanent sales are commonplace in at least six: the Mojave, Chino, Central, Raymond, Tehachapi, and West Coast basins.

In the early 1990s, the California legislature enacted AB 3030, legislation to allow certain defined existing local agencies to develop a groundwater management plan (GMP) in groundwater basins.[6] These agencies are granted authority to regulate groundwater activities within the basin, make infrastructural investments, and procure supplemental water for artificial recharge. Groundwater management plans may include rules or components related to twelve technical issues, including prevention of seawater intrusion, mitigation of conditions of overdraft, well abandonment and destruction, and remediation of pollutants, among others. However, these agencies are not able to make determinations of water rights, and they may

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[4] Local ordinances passed by municipalities and counties to exert control through the permitting process also exist. These entities cannot make determinations on water rights; however, recent cases have provided evidence that the police powers of these authorities allow pumping restrictions (see Allegretti vs. County of Imperial, 2006). Given their nascent and uncertain role in restricting pumping, these ordinances are not included in the analysis.

[5] Adjudication can be initiated either by lawsuit or by cooperative negotiations between all (or most) users. Previously, the exact number or proportion of parties that would need to stipulate to a judgement for a court to accept it was not specified by law. In addition, stipulated judgements could not always be imposed on objecting parties (see the Cardozo Group in the Mojave Basin adjudication). However, Assembly Bill 1390 (AB 1390), passed in 2015, sets forth proportions of 50% of all extractors who are responsible for 75% of all extractions (in the five years preceding adjudication) as the minimum support for a comprehensive adjudication. In these cases, the proposed stipulated judgement will apply to any and all objecting parties.

[6] Defined in DWR Bulletin 118. No new level of government is formed. Action is voluntary not mandatory. This is the original Groundwater Management Act (GMA).

not restrict pumping unless they can show that replenishment activities are insufficient to lessen the demand for groundwater (Sec. 10753.8 (c)).[7]

In reality, GMPs drafted under AB 3030, and knock-on legislation SB 1938 and AB 359, have not resulted in stringent groundwater controls. Despite having the authority to assume the powers of a water replenishment agency – namely, to levy assessments on water users to finance the acquisition of replenishment water – to date only one such water replenishment district exists in California, and it was not formed under AB 3030.[8] Many GMPs do not propose more than the implementation of improved monitoring systems. To our knowledge, no GMPs have been successful in implementing production restrictions. In summary, groundwater management plans drafted under AB 3030 have been described as "very weak" and a way for often inconsequential changes to be implemented with very little opposition (McGlothlin, 2016).

III. Conceptual Model

In this section we describe a conceptual model of the problem faced by groundwater users when considering the implementation of groundwater management controls. This includes the benefits to users of adopting institutional structures to alleviate common-pool losses as well as the bargaining costs associated with these transitions

Benefits via Alleviated Common-pool Losses

Maximizing the rents from a CPR can be a complex optimization problem over space and time, and rent dissipation occurs when an alternative method of production exists with higher benefits net of all costs, including the costs of implementing the new production regime. We examine five categories of factors changing the level of common-pool rent dissipation under open access: (1) commonality, the degree to which the resource is actually shared as a common pool; (2) value, the extent to which better allocating an additional unit of the resource increases rents; (3) heterogeneity, a measure of the degree to which allocations changing the spatial, temporal, or type of use are available; (4) degradation, the potential for damage to occur to the physical resource system; and (5) growth, a measure of the potential for intertemporal reallocation.

Common-pool losses arise in groundwater basins because the legal doctrine of correlative rights closely resembles open-access—the volume of water pumped in any given year is not restricted except by loosely interpreted beneficial and reasonable use requirements. Under open access, pumpers extract groundwater until the marginal private costs of doing so equal the marginal benefits. However, the socially optimal rate of pumping is characterized by each user extracting to the point that marginal private benefits are equal to the aggregate social cost incurred by his/her pumping. Broadly speaking, this over-pumping can exacerbate three problems: (1) over-extraction because the value of water in the future and to other users is not properly accounted for, (2) local spatial effects of pumping increase pumping costs

[7] Plans proposed by local agencies to the Department of Water Resource (DWR) must not be opposed by a majority of the assessed value of landholdings within the basin. Should no such opposition exist, the plan may be adopted within 35 days; however, if the plan is opposed it must be abandoned and no new plan may be suggested for one year. In addition, the decision to levy fees or assessments must pass a majority vote according to the voting rules of the agency or laws regarding local elections.
[8] http://www.wrd.org/about/water-district-history.php

for nearby users,[9] and (3) collateral effects of aquifer drawdown can jeopardize resource quality or have other costs (e.g., seawater intrusion, subsidence).

We do not attempt to measure these avenues of rent dissipation directly in order to assess the benefits of adopting groundwater management; indeed, they are endogenous to the institutions we intend to study. Instead, we develop measures of the underlying factors that increase these losses, independent of management, and assume that these resource-specific pathways describe the nature of the common-pool losses to be avoided by implementing management institutions.

Figure 1 presents an exemplary aquifer system to illustrate these relationships more clearly. Users A through G overly the aquifer. When water is scarce in areas of low precipitation and recharge, the groundwater resource is more **valuable** and the benefits of institutional controls will be higher, all else equal (Edwards, 2016). Likewise, plentiful surface water resources (either native or imported) reduce the relative value of groundwater. This value of the resource determines the extent of losses through misallocation of production across uses and time – development of tradable property rights can alleviate these losses.

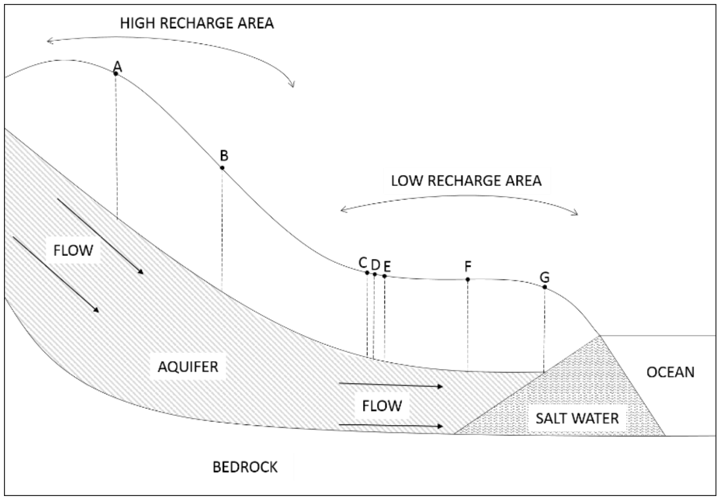
The extent to which pumping effects are transmitted between users is determined by **hydraulic conductivity (commonality)**, the rate at which water flows in the aquifer, and distance. Users C, D and E are located in close proximity and may face severe local spatial effects, and rent losses, due to well interference (Guilfoos et al., 2013; Brozovic et al., 2010; Edwards, 2015). The pumping interaction between users E and F may be less severe, but rent dissipation is still likely when hydraulic conductivity is high. Meanwhile, higher commonality can also increase rent dissipation through effects on surface water sources. When groundwater is pumped, especially near a stream, streamflow is reduced. In this way, higher surface water availability can increase the returns to adjudicating groundwater rights.

In addition, collateral **degradation** of the aquifer is also a concern. Water quality can be jeopardized when salt water intrusion reaches wells, shown here for user G. Basins where this is a concern have a higher potential for degradation and can dissipate rents along this margin. Better management of pumping, and even artificial recharge, can create a buffer to protect coastal users. Zekri (2008) finds that in the Batinah coastal area of Oman unmanaged seawater intrusion could result in $288 million in losses.

Different levels of water demand can also lead to rent losses under open access. If users C,D, and E have a high demand for water, potential gains from trade can occur if they are able to pay users B and F not to pump. Absent institutional control, users B and F see no incentive to reduce consumption under the correlative rights doctrine. **Heterogeneous marginal product of water** across users, for instance between urban and agricultural users, can create heterogeneous demand. Worthington et al. (1985) show that common pool losses may be nearly 30% when farmers on the Crow Creek Valley Aquifer System in Montana have heterogeneous land productivity. **Growing demand** can also create heterogeneous demand across time. It may be socially valuable for areas with high recharge not to consume all their water, instead allowing it to move through the system over years or decades to be consumed in areas with less water. Brill and Burness (1994) show common pool losses as high as 17% in eastern New Mexico when demand growth is present. Institutional control over the resource can facilitate this process and lead to aggregate gains. For instance, users A and B could be paid to forgo pumping to allow more water to flow to users C D, and E.

[9] When pumping occurs, a cone of depression is formed that lowers either the water level or the potentiometric surface (pressure) in a radius around the well. This can impede extraction by nearby users.

Figure 1: Illustrative Representation of a Physical Aquifer System



To summarize, characteristics of aquifers and users determine the extent to which correlative rights lead to rent dissipation. The magnitude of these common-pool problems determine the aggregate benefits of increased institutional control over groundwater use.

Table 1 provides groundwater-specific measures of these factors, what variable from the theoretical framework it represents, and the predicted effect on the magnitude of common-pool losses of an increase in that measure.

Table 1: Predictions of the Determinants of Common-Pool Losses

Measure	Measure of:	Predicted Effect
Hydraulic Conductivity	Commonality	+
Surface Water Availability	Value	-/+
Precipitation/Recharge	Value	-
Spatial Recharge Variance	Heterogeneity	+
Density of Local Wells	Heterogeneity	+
Risk of Seawater Intrusion	Degradation	+
Risk of Subsidence	Degradation	+
Percent Urban Land Use	Heterogeneity	+
Population	Value/Growth	+
Population Density	Growth/Heterogeneity	+
Population Growth	Growth	+
Production of Permanent Crops	Value/Heterogeneity	+

Bargaining Complexity and Costs

The decision to adopt groundwater management regulations, however, is not made purely on the basis of whether aggregate net gains exist. Individual actors will support or oppose various institutional arrangements based on private net benefits. Broadly speaking, bargaining complexity will be determined by (1) the number of users; (2) the size and heterogeneity of the resource, as well as how well informed users are about its characteristics; and (3) heterogeneity across parties that influences their bargaining positions.

In the event that users are heterogeneous in marginal products of water as well as the degree and type of common-pool losses they incur, bargaining over which rules to adopt or whether to adjudicate rights will be costly. For example, pumpers closer to the coast will be more likely to support pumping restrictions because they are at most risk of seawater intrusion while those on the interior may be recalcitrant. Likewise, pumpers in areas with high well density will be likely to support regulations that reduce local spatial externalities. Institutions also vary in their costs of implementation. Depending on which institutional design is under consideration, some users may see net losses while others benefit. In this setting, side payments may be necessary to establish cooperation. Where bargaining costs are high, basins that might otherwise achieve large aggregate benefits of management may not succeed in implementing new institutional regimes. Table 2 lists factors that may affect these bargaining costs, including the number of bargaining parties and measures of heterogeneity that may affect their demand for water and exposure to common-pool losses.

Table 2: Predictions of the Determinants of Bargaining Costs

Variable	Measure of:	Predicted Effect
Basin Size	Resource Size and Characteristics	+
Number of Users	Number of Users	+
Variance in Number of Wells/Users	User Heterogeneity	+
Proportion of Urban vs. Ag Use	User Heterogeneity	+
Heterogeneity in Relative Position (Upstream/Downstream, to Coast)	User Heterogeneity	+
Variance in Size of Farms	User Heterogeneity	+
Spatial Recharge Variance	Resource and User Heterogeneity	+
Well Yield	Resource Size and Characteristics	+

Basin size is likely to increase bargaining costs because larger basins present greater logistical problems associated with notifying and bringing together parties; also, larger basins are more difficult to monitor, which increases the costs of reaching agreement on knowledge about the resource. Higher hydraulic conductivity increases bargaining complexity because those in areas of dense well spacing will be more likely to support production restrictions. Dimensions of heterogeneity amongst resource users also affect costs. Urban users have longer planning horizons and more inelastic water demand than agricultural users, which will influence their bargaining positions. Urban users will be less willing to implement pumping reductions. Users with more wells may stand to benefit more from management, either because they pump more in aggregate or because they are more exposed to local pumping interference.

Several spatial variables are also important. The relative position of pumpers matters; pumpers located upstream, where groundwater recharge naturally flows to other users, will be less supportive of production restrictions that allow groundwater to flow away from them. Similarly, if a large pumping contingent is located inland but the basin is exposed to seawater intrusion, those who pump inland will be unwilling to restrict production because they do not bear the costs of this potential aquifer degradation.[10]

[10] The Santa Maria Valley adjudication presents a nice anecdote for this type of complexity. Inland agricultural users were recalcitrant during negotiations and appealed the case to the State Supreme Court – the adjudication ended up taking eleven years and costing tens of millions of dollars.

Spatial variance in recharge also matters because pumpers with access to plentiful and regular recharge will not ascribe the same scarcity value to the resource as those in areas that depend more upon subsurface flow to access groundwater.

IV. Data and Empirical Strategy

Data

Data were collected on aquifer and user characteristics for California's 430 groundwater basins. Variables including units of measurement and source are found in Table 3. Table 4 presents summary statistics. They are tabulated below based on whether they affect benefits or costs, although some variables, such as well yields and urban land cover, are presented as measures of basin or user characteristics that could influence both the benefits as costs. Some variables exhibit large differences in conditional means across the different management types. This is represented graphically in Figure 2 in Section V.

Table 3: Data Descriptions and Sources

Variable	Units	Source
Benefit Factors		
Surface Water Availability	Highest stream order	*USGS*
Population (1950-2010)	Levels, density, growth rate	*CA Dept. of Finance*
Precipitation (1950-2014 mean)	Millimeters	*PRISM*
Distance to Coastline	Meters from nearest point	*DWR*
Cost Factors		
Surface Area	Acres or sq. miles	*DWR*
Farm Size (mean)	Acres	*USDA (forthcoming)*
Farmed Area	Acres	*USDA (forthcoming)*
Number of Farms	Count	*USDA (forthcoming)*
Affecting Both Benefits and Costs		
Well Yield (Max/Average)	Gal/min	*DWR*
Urban Demand – Proxy via land cover	Acres or percentage	*DWR and CalTrans*
Precipitation (1950-2014 spatial variance)	Millimeters	*PRISM*
Other		
Number of GMPs	Number (also: dummy if >0)	*DWR*
Adjudication	Dummy	*Author's data*

Table 4: Summary Statistics, Mean and (standard deviation), by Groundwater Institution

	Adjudicated	GMP	None	Total
Number of Basins	*32*	*91*	*311*	*430*
Basin Size (acres)	145,652	207,126	52,540	92,184
	(204,795)	(1,002,996)	(125,798)	(479,070)
Percent Urban (2010)	40.1	23.3	14.6	18.4
	(41.3)	(32.7)	(32.2)	(33.7)
Distance to Coast (miles)	56.8	83.3	99.4	92.8

	(43.7)	(69.2)	(88.4)	(82.8)
Highest Stream Order (#)	1.75	1.42	1.24	1.32
	(1.1)	(1.24)	(1.22)	(1.22)
Well Yield (maximum)	2,450	1,816	1,150	1,493
	(2,313)	(1,705)	(1,288)	(1,633)
Well Yield (average)	710	565	432	502
	(495)	(541)	(556)	(550)
Population (1950)	112,075	21,702	3,305	15,293
	(483,263)	(115,469)	(44,398)	(147,951)
Population (2010)	381,169	129,555	9,218	62,365
	(1,192,681)	(526,502)	(54,329)	(416,666)
Precipitation (mean)	337	469	533	505
	(161)	(294)	(445)	(405)
Precipitation (spatial variance)	4,027	3,427	2,945	3,127
	(6,113)	(5,580)	(5,127)	(5,300)

"Basin size" is a measure of the surface area overlying the aquifer. "Percent urban" measures the percentage of this surface area that is in urban land uses. "Distance to coastline" is measured from the nearest point of the aquifer to the ocean, and "highest stream order" reports the highest order stream found within the basin.[11] Well yield data were compiled by the California Department of Water Resources (DWR) and proxy for hydraulic conductivity. Our population measures report urban population numbers within a basin – if a city's center is located within the land area overlying the basin, its population was included. Finally, the precipitation variables were constructed from historical spatial interpolations of precipitation data produced by Oregon State University's PRISM Climate Group.[12] Precipitation patterns within the land area overlying the aquifer were used.

Estimating Factors Increasing Benefits of Institutional Control

For a groundwater basin, i, we would like to observe the benefits of stronger institutional controls, Y_i^*. Instead, we only observe whether a basin has selected a particular set of institutional controls: none, groundwater management district, or adjudication. Because the types of management have different costs associated with them, we can link them to different levels of benefits via an ordered logit model. Consider a vector of n characteristics of a groundwater basin, X_i. The benefits of management are determined by these characteristics according to the following relationship:

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

Where u_i is assumed to be distributed standard logistic. Now define Y_i as the level of management, where $Y_i = \{1,2,3\}$ represents {None, GMD, Adjudicated}. The value of Y_i is determined by the unobserved latent variable, Y_i^*, according to the following:

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

[11] Stream order is based, loosely defined, on the number of tributary confluences upstream of a reach of river. If two "first-order" streams with no tributaries meet, their confluence is referred to as a "second-order" stream. Two second-order streams meeting produces a third-order stream, and so on. In general, higher-order streams have higher flows and more water available.

[12] http://www.prism.oregonstate.edu/

$Y_i = 2 \ if \ \kappa_1 \le Y_i^* \le \kappa_2$

$Y_i = 3 \ if \ \kappa_2 \le Y_i^*$

Where κ_1 is the cost of implementing a groundwater management district, κ_2 is the cost of implementing adjudication, and $\kappa_1 \le \kappa_2$—it is more costly to switch to be adjudicated than to implement a groundwater management district. The probability of a basin being in a particular level of management is:

$$\Pr(Y_i = q) = \Pr\left(\kappa_{q-1} < Y_i^* \le \kappa_q\right) = F(\kappa_q - X_i'\beta) - F(\kappa_{q-1} - X_i'\beta)$$

Because we have assumed the distribution of the error terms is logistic, the logistic CDF is used:

$$\mathrm{F}(z) = \frac{e^z}{1+e^z}$$

Let $I_{iq} = 1$ when $Y_i = q$, then the log likelihood function is:

$$l(\kappa, \beta) = \sum_{i=1}^{n}\sum_{q=1}^{3} I_{iq} \ln\left[F\left(\kappa_q - X_i'\beta\right) - F\left(\kappa_{q-1} - X_i'\beta\right)\right]$$

$$= \sum_{i=1}^{n}\sum_{q=1}^{3} I_{iq} \ln\left[\frac{e^{\kappa_q - X_i'\beta}}{1+e^{\kappa_q - X_i'\beta}} - \frac{e^{\kappa_{q-1} - X_i'\beta}}{1+e^{\kappa_{q-1} - X_i'\beta}}\right]$$

The parameters $\hat{\kappa}_1, \hat{\kappa}_2, \hat{\beta}_1, \hat{\beta}_2, \dots, \hat{\beta}_n$ are estimated by maximizing this function. Because these parameter estimates are based on the latent variable, Y_i^*, they tell us important information about the how the variables in X increase or decrease the benefits of adjudication. The estimates of the $\hat{\beta}$'s tell us whether an explanatory variable increases or decreases the benefits of more institution control over groundwater. The $\hat{\kappa}$'s provide information on the difference in the costs between different levels of management.

Table 5 provides each variable included in the ordered logit, what variable from the theoretical model it represents, and its predicted sign.

Table 5: Predicted signs on $\hat{\beta}$s

Variable	Measure of:	Predicted Sign
Well Yield	Conductivity	+*
Precipitation	Recharge	-
Spatial Variance in Precipitation	Heterogeneity	+*
Distance to Coastline	Seawater Intrusion	-
Percent Urban	Demand Growth	+*
Population 1950	Demand Growth	+
Population Density	Demand Growth	+
Population Growth	Demand Growth	+
Basin Size	Bargaining Costs	-

*Because this is also a proxy for demand heterogeneity and could increase bargaining costs, the sign of its net effect is ambiguous.

Estimating Factors Increasing Costs of Bargaining

Different institutional rules govern how bargaining takes place for adjudication and the adoption of a GMP. Specifically, adjudication requires participation in judicial proceedings, which requires time and money for representation, while GMP formulation is undertaken by a local public agency in consultation with stakeholders, and opposition is registered in a formal sense only after the GMP has been proposed. The expenditures of the parties to an adjudication or GMP adoption process are not observed directly,[13] but a proxy for total costs exists in the duration of the adjudication process. From the time that court documents are filed to the finalization of the judgement, parties and their lawyers are engaged in a judicial bargaining process over the form of the stipulated judgement. To the extent that judgements are appealed or that certain, important parties remain recalcitrant, the process draws on and additional costs are incurred. It may be the case that some costs are incurred during informal negotiations prior to the submittal of court documents, but they are likely much lower than the costs associated with the judicial process.

We observe the duration of the adjudication process for each adjudicated basin. These duration data lend themselves to the application of a Cox Proportional-Hazard Model (Cox PH). Duration analysis can be used to examine how long basins require to exit the state of being in adjudication proceedings. Econometrically, duration analysis involves the estimation of a hazard function. The hazard function represents the probability of completing the adjudication, conditional on having already survived some amount of time from the initial state (as such, the hazard rate can vary with time). Formally, this 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. Additionally, X is the vector of covariates and λ_0 represents the underlying 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. For example, the parameter of the proportional hazard function associated with hydraulic conductivity might indicate that having higher conductivity affects the length of the adjudication process. In this case, $\kappa(\cdot)$ is not a function of time because we assume covariates are time-invariant and their effects are constant across time. Table 6 provides each variable included in the Cox PH, the predicted sign of the coefficient, and the predicted effect on the expected length of duration of an increase in that covariate.

Table 6: Predicted signs on $\hat{\boldsymbol{\beta}}$s

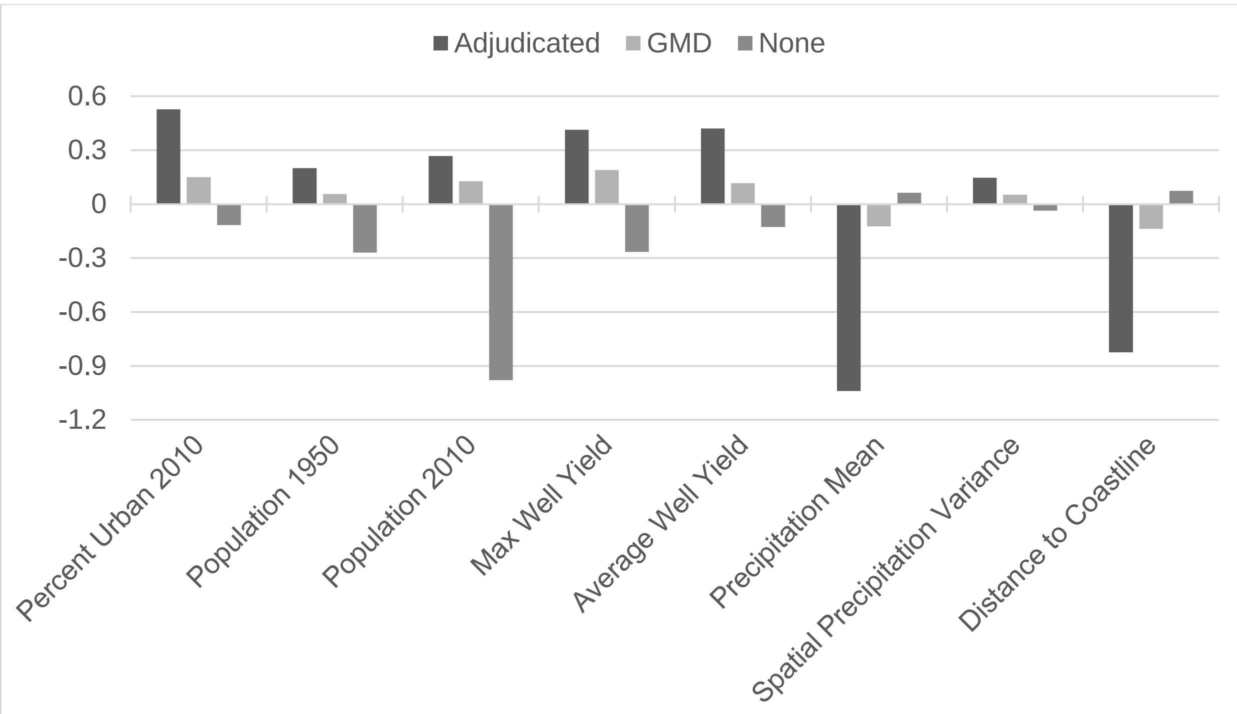
Variable	Predicted Sign
Basin Size	- (Longer)
Mean Spatial Recharge Variance	- (Longer)
Average Population Growth 1950-2010	- (Longer)
Percent Urban	- (Longer)
Well Yield	- (Longer)
Mean Precipitation 1950-2014	Control

[13] Parties may spend money on bargaining, but they also contribute time, and in some cases the costs of bargaining are reflected simply in the failure to reach agreement. Proxies for costs are the next best alternative.

V. Results

Figure 2 provides t-statistics comparing the means of each of the three levels of groundwater controls to the overall sample mean. The predictions indicate that benefits are increasing in the population variables, well yield variables, and the spatial precipitation variance variable. Adjudicated basins have the highest means for each of these variables, and basins without institutional controls have the lowest means, providing a clear illustration of the ordered nature of the data. For the variables with an expected negative relationship (precipitation and distance to coastline) the reverse relationship is observed.

Figure 2: Normalized Distance from Mean (t-statistic)



To test these relationships statistically, the ordered logit model is applied. The results of several different specifications are shown in Table 7. The first four specifications use well yield, a measure of conductivity, which is only available for 209 of California's groundwater basins. The fifth specification drops well yield, allowing the use of all 430 of the basins. [14]

[14] The ordered logit model relies on a parallel slopes assumptions, 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 in the first four specifications; the fifth can be rejected at the 5% level. The first four specifications are thus more consistent with the assumptions of the model.

Table 7: Ordered Logit Regression Results: Net Effects

	(1)	(2)	(3)	(4)	(5)
	Mgt Type	Mgt Type	Mgt Type	Mgt Type	Mgt Type
Max Well Yield	0.000286***	0.000300***	0.000307***	0.000283***	
	(0.000102)	(0.0000978)	(0.000108)	(0.000104)	
Percent Urban Land Use 2010	0.00819			0.00920*	0.00742**
	(0.00515)			(0.00500)	(0.00372)
Basin Size	-3.90e-08	-0.00000011*	-7.42e-08	-2.82e-08	0.0000002**
	(6.29e-08)	(6.39e-08)	(6.33e-08)	(6.20e-08)	(9.97e-08)
Mean Precipitation 1950-2014	-0.00110**	-0.00112**	-0.00121**	-0.000390	-0.00164***
	(0.000545)	(0.000542)	(0.000537)	(0.000482)	(0.000386)
Mean Spatial Precip. Variation 1950-2014	0.0000643*	0.0000534	0.0000612*		0.0000665***
	(0.0000378)	(0.0000372)	(0.0000353)		(0.0000241)
Distance to Coastline	-0.00445*	-0.00596***	-0.00647***	-0.00421*	-0.00451***
	(0.00264)	(0.00210)	(0.00215)	(0.00248)	(0.00157)
Average Pop. Growth 1950-2010		0.00887			
		(0.00697)			
Population Density			0.185		
			(0.234)		
Mean Spatial Precip. Coeff. of Var.				2.095	
				(1.557)	
Kappa 1	0.529	0.279	0.179	0.932*	0.114
	(0.462)	(0.389)	(0.375)	(0.508)	(0.308)
Kappa 2	2.066***	1.814***	1.703***	2.459***	1.828***
	(0.527)	(0.463)	(0.438)	(0.566)	(0.363)
Observations	209	209	209	209	430

Standard errors in parentheses

* p< .1, ** p< .05, *** p< .01

The results in Table 7 represent the net effects of these covariates; some, such as well yield, affect only the benefits, while others, such as the spatial distribution of recharge, may affect both benefits and bargaining costs. Across all specifications, coefficients on precipitation and distance to coast have the expected signs. Additionally, measures of urban land use, maximum well yields, and the spatial variance in precipitation have positive signs, suggesting that, on average, their net effects are to increase the benefits of instituting management. Of these variables, well yields, precipitation, distance to coastline, and the spatial variance in recharge are in most specifications statistically significant and can be said to reliably affect the likelihood of either adopting a GMP or adjudication groundwater rights. This is consistent with the predictions of our conceptual model that increased commonality, heterogeneity, and potential for degradation increase the benefits of adopting groundwater management institutions, while increased precipitation, leading to a lower relative value of groundwater, decreases the benefits.

Table 8 presents estimates of the marginal effects of the variables that were statistically significant in model specification (1), in addition to the percent of urban land use. The marginal effect of well yield leads to the greatest change in probability: a one standard deviation change increases the probability of falling into the adjudicated category by 4.73 percentage points and into a GMP by 6.17 percentage points. The unconditional probability of being adjudicated is around 11% and of having a GMP of around 26%. Therefore, the magnitude of changing any of the variables in Table 8 by a full standard deviation on adoption of adjudication or a GMP will be substantial relative to the underlying probability of adoption.

Table 8: Marginal Effects in Percentage Points

	Max Well Yield	Mean Precipitation	Distance to Coast	Urban Land Use	Spatial Precip Variance
One Standard Deviation around Mean					
None	-10.91%	8.75%	7.49%	-6.67%	-7.56%
GMP	6.17%	-4.96%	-4.25%	3.79%	4.29%
Adj.	4.73%	-3.79%	-3.24%	2.88%	3.27%
One Unit Increase at Mean					
None	-0.007%	0.026%	0.104%	-0.192%	-0.002%
GMP	0.004%	-0.015%	-0.059%	0.109%	0.001%
Adj.	0.003%	-0.011%	-0.045%	0.083%	0.001%

The interpretation of some other coefficients is more difficult. The effect of basin size, for instance, is tricky. The negative sign on this coefficient in most specifications is consistent with our hypothesis that it increases bargaining costs and has a net negative effect on the likelihood of adoption of management. However, the fact that it is only statistically significant in two specifications and flips sign when the well yield covariate is removed suggests that it isn't a reliable predictor. Meanwhile, alternative measures of demand heterogeneity (population growth and density) as well as spatial heterogeneity in recharge (using a coefficient of variation rather than variance) have identical signs but are statistically insignificant.

Table 9 presents results from the Cox PH regressions on the duration of the adjudication process. Columns 1 and 2 present results for all adjudicated basins, omitting well yield data. Columns 3 and 4 include well yield data for a restricted sample. Despite small sample sizes, we observe statistically significant results for several covariates.

Table 9: Cox Proportional Hazard Regression Results

	(1)	(2)	(3)	(4)
	Adj Duration	Adj Duration	Adj Duration	Adj Duration
Basin Size	0.00000150	0.00000176*	0.00000211**	0.00000257***
	(0.00000135)	(0.000000994)	(0.000000936)	(0.000000872)
Mean Precipitation 1950-2014	-0.00158	-0.000543	-0.000673	-0.00124
	(0.00111)	(0.00101)	(0.00123)	(0.00128)
Mean Spatial Precip. Variance	0.0000468**	0.0000327*	0.00000403	0.0000121
	(0.0000193)	(0.0000192)	(0.0000264)	(0.0000240)
Average Population Growth 1950-2010	-0.00210		0.00472	
	(0.00296)		(0.00519)	
Percent Urban Land Use 2010		-0.00774		0.00482
		(0.00517)		(0.00725)
Well Yield Average			-0.00131**	-0.00144**
			(0.000578)	(0.000689)
Observations	32	32	23	23

Standard errors in parentheses

* p< .1, ** p< .05, *** p< .01

When interpreting coefficients in a Proportional Hazard models, it is important to recall that they affect the hazard rate; in other words, a positive coefficient implies a positive marginal effect on the hazard rate, which, all else equal, will reduce the expected length of an adjudication process. Accordingly, the significant but positive coefficients on basin size and spatial variance in recharge imply a shortened duration and run counter to our hypotheses. Notably, once we control for well yields (and reduce the sample size slightly), the effect of the spatial variance in precipitation loses significance. Well yields are a better predictor in these specifications. Meanwhile, measures of urban land use and population growth are insignificant. These were hypothesized to increase bargaining costs, so the sign is correct when we do not control for well yields but incorrect in the last two specifications. All in all, these measures provide no evidence to support our hypothesis that more heterogeneous demand increases bargaining costs. This may be masking the effect of heterogeneity because demand is actually more homogeneous at high levels of urban use. Alternative measures should be considered.

The effect of increased hydraulic conductivity, as measured by well yields, is consistently significant and implies longer durations and higher bargaining costs. This is the only result from the Cox PH estimation that supports our hypotheses. A higher average well yield, which indicates higher hydraulic conductivity, may accentuate well interference problems and interactions between surface and groundwater within the basin. It may be that a subset of users is more exposed to either well interference (spatial heterogeneity in well density would be consistent with this) or losses from reduced streamflow (e.g., in a basin where surface water diversions are important for some users). In that case, that subset would be more willing to support stringent pumping controls, and this heterogeneity in bargaining positions increases bargaining costs.

VI. Conclusions

Common-pool resources are often subject to overuse and depletion when open-access conditions prevail. Institutions that restrict the number of users, constraint their levels of extraction, and regulate how the resource may be accessed – such as property rights – offer users the opportunity to increase rents and limit resource degradation. However, not all CPRs are created equal. Because action to limit open-access conditions is costly for many CPRs, a tradeoff exists, and some resource users may be better off not adopting new management regimes. Broadly, we expect the adoption of management where the benefits of regulating use exceed the costs of implementing new regimes and reaching consensus over their form and scope.

Our results indicate that hydraulic conductivity, regular levels of precipitation and recharge, the spatial distribution of this recharge, and the risk of exposure to seawater intrusion reliably explain the adoption of more stringent groundwater management institutions in California. Moreover, within our conceptual framework, these results provide evidence that the value of water, the commonality of the groundwater resource, and the potential for resource degradation all influence the nature and degree of common-pool losses that can be expected under open-access regulatory conditions. Alleviating these losses by altering the institutional structure of resource access to address incentives to over-pump generates benefits for resource users.

On the cost side, results are less conclusive. A larger basin size reduces the likelihood of adopting management in the ordered logit results, although it is statistically insignificant. However, our duration analysis suggests that it may shorten adjudication time. This conflicting evidence does not immediately support our hypothesis that users in larger basins face higher bargaining costs. This could be a result of the failure of adjudication time to faithfully proxy bargaining complexity. More data on user heterogeneity and will allow us to identify more of the determinants of bargaining costs.

Meanwhile, higher hydraulic conductivity reliably explains, in addition to higher benefits of management, longer adjudication times. This suggests that more commonly held aquifers are associated with higher bargaining costs, perhaps because a subset of users is thereby more exposed to well interference effects. On balance, it is clear that hydraulic conductivity increases the benefits of adjudication, and evidence suggests that it may increase bargaining costs as well. This is one of our strongest predictors of adoption. On average, the net effect appears to be positive.

We make a contribution to the literature on common-pool resource management by identifying specific basin and user characteristics that increase the benefits of implementing institutional remedies to common-pool losses; in addition, we hope to contribute to the literature on institutional formulation and evolution by describing what makes bargaining over new institutions complex and difficult.

Finally, these results can inform the implementation of California's new groundwater legislation, the Sustainable Groundwater Management Act (SGMA) of 2014. This legislation foresees that medium- and high-priority basins may choose for themselves the best way to achieve sustainable resource use; the adoption of GMPs and the adjudication of groundwater rights are two avenues that basin users may consider. The institutional structure of resource access is likely to change in these basins as a result of this legislation, so understanding the characteristics of aquifers and their users that influence the returns to and difficulty of formulating management institutions will allow us to make recommendations about what type of management is appropriate. Demonstrating where adjudication can be extremely costly or shedding light on the types of common-pool problems for which less stringent restrictions are appropriate could improve the implementation of SGMA considerably.

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