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The Economic Value of Secure Water: Landowner Returns to Defining Groundwater Property Rights

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Abstract:

Groundwater is a prime example of a common-pool resource subject to over-extraction and rent dissipation under open access. To avoid this, users can assign groundwater rights: a cap is set on the volume of groundwater that can be pumped annually, and rights are allocated among users. Although this process restricts pumping, it also improves long-term resource availability, grants a fungible asset that can be traded, and reduces uncertainty for urban developers. We investigate the effect on land values by exploiting a plausibly exogenous discontinuity in the definition of rights in the Mojave groundwater basin in California. Because both the long-term stream of agricultural rents and the value of tradable permits are capitalized into land value, spatial regression discontinuity designs identify the difference between the value of interior parcels with water rights and those of free riders on the exterior, who can drain from the regulated area with no restrictions. We find that the value of rights outweighs gains realized by free riders and that property rights increase land value by half. The large gains estimated here support the idea that the allocation of rights may be instrumental in convincing otherwise recalcitrant users to accept restrictions.

JEL Codes: D02, K11, Q25, Q15

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I. Introduction

Common-pool resources are subject to excessive exploitation and rent dissipation in the absence of well-defined economic property rights (Gordon, 1954; Hardin, 1968; Ostrom, 1994). In the absence of transaction costs, fully defined rights allow users to bargain among one another to reach an efficient allocation of resource use (Coase, 1960); the resource is used in its most efficient production processes. This can improve outcomes in a variety of resource settings, including increasing harvested value from fisheries, reducing pumping costs in groundwater aquifers, and improving forestry yields. Nonetheless, in many cases new institutions are not adopted because some users do not perceive a benefit (Libecap and Wiggins, 1984; Wiggins and Libecap, 1987), which suggests the need for better understanding of when returns are likely to be positive and economically meaningful.

Although the establishment of property rights holds promise for alleviating resource depletion and rent dissipation that result from the tragedy of the commons, few investigations have rigorously documented the economic value of gains from property rights (exceptions are from fisheries: see, for example, Grafton et al., 2000). Water is a critical resource for humanity, and groundwater in particular regularly suffers from poor institutions and mispricing. Our work helps to further understanding of the impact of tradable property rights on the value of natural resources by looking at a complementary input (land) to assess the impact of property rights to groundwater. Because water access is often appurtenant to land, its value can be reflected in land prices (Buck et al., 2014; Yoo et al., 2013). Where water is a critical input for agricultural production and urban development, do land prices change when property rights are assigned to users of a common pool of groundwater?

Identifying the true effect of water institutions on land value is difficult because there are so few examples of their adoption and endogeneity concerns complicate inference in direct cross-sectional comparisons. In California, some groundwater basins have been adjudicated, meaning that tradable volumetric pumping rights[3] have been established and allocated to individual users. We look to the Mojave Basin in southern California, which completed adjudication proceedings in 1996 and where groundwater represents a major constraint on agricultural and development activity. Our empirical approach exploits plausibly exogenous variation in the boundary of the adjudicated area—and thus the extent of the adjudication rules—to identify part of the effect of groundwater adjudication on land values.

Theory suggests two pathways for groundwater adjudication to affect land values: First, for those in the regulated area, tradable property rights capitalized into land value result in a wealth effect for users holding rights, and the present discounted value of future agricultural rents increases because the water table stabilizes. Second, free riders along the fringe can drain groundwater from within the regulated area and thereby enjoy an agricultural rent premium. The spatial regression discontinuity we implement compares parcels overlying the aquifer across the adjudication boundary, subtracting this second effect from the first; whether the outcome is positive or negative is theoretically ambiguous and depends on resource characteristics and the marginal value of water.

This discontinuity coefficient represents a lower bound on the effect of groundwater property rights. Results suggest that the net effect is positive and, in some cases, results in a 40-50% increase in land value within the adjudicated area. Furthermore, heterogeneous treatment

3 These rights are defined as a share of a "safe yield" cap that can be pumped from the basin in each year and are measured in acre-feet/year. Depending on the adjudication, the total safe yield may vary interannually, but it is generally set at the amount of pumping that will stabilize water levels in the long term.

effects across adjudicated subareas, between which trades are prohibited, suggest there may be a role for anticipated urban demand in determining the magnitude of economic gains.

This work contributes to the literature on common-pool resource management by documenting a portion of the returns to collective action to restrict open-access extraction rates. These estimates are the first to address the returns to groundwater property rights, and moreover the first to use parcel-level data to examine the returns to groundwater management more broadly. Aside from demonstrating that expected returns can be economically meaningful when groundwater is a constraining factor for agriculture and development, these results illustrate how gains for cooperators depend on resource characteristics and demand growth, providing guidance for where agreement on institutions should be easy to reach. In particular, the adjudication of the Mojave groundwater basin was very difficult, with a failed attempt in the 60s and appeals to the State Supreme Court before final success in the 90s. The large estimated gains here may document a case in which urban areas wishing to solve the common-pool problem and grow in a water-constrained area agreed to grandfather rights to agricultural users in order to overcome bargaining difficulties.

Furthermore, this work has implications for California's Sustainable Groundwater Management Act (2014). This legislation requires basin users to ensure sustainable use of groundwater resources; for many basins, this will require adjudication, which is a costly process (Ayres et al., 2017). Oftentimes, complications that inhibit agreement on management arise from uncertainty about how reduced groundwater withdrawals will affect future agricultural production and land value. As the first estimate of the effect of groundwater adjudication on agricultural land values, this research can help reduce uncertainty about the expected returns to landowners and promote more sustainable groundwater management through markets.

II. Background

A. Motivation

Sound management of common-pool resources, such as shared timber stocks, fisheries, and groundwater aquifers, is critical for economic development and the welfare of resource-dependent populations. Where property rights are poorly defined, and especially under open-access conditions, incentives for efficient resource use and investment are threatened because any resource value not extracted can be captured by other users. This results in a race to extract and rent dissipation; however, institutions that better define economic property rights can address the problem (Gordon, 1954; Hardin, 1968; Ostrom, 1994). The definition of legal property is one avenue to resolve the problem because it allows users to restrict both individual and aggregate use and reallocate it through trading (Coase, 1960). Users themselves often initiate the formation of rights. In defining property rights, users attempt to increase the value of the resource by restricting aggregate extraction, enriching themselves in the process because they remain residual claimants to the resource.

The economic literature has long stressed the importance of residual claimants in the management of natural resources, but empirical estimation of the benefits of adopting legal property rights are few, especially in the case of groundwater. One example comes from fisheries: Grafton et al. (2000) demonstrate that rationalizing the British Columbia halibut fishery led to increased efficiency and greater resource rents, in particular due to the ability to market higher-quality fishery products. This result suggests gains for rights holders and the fishery overall despite restricted resource access; tradable property rights to harvest certain numbers of fish outperformed both open access and a costly regulatory approach. In this paper, we ask whether property rights to groundwater create similar returns for landowners.

Groundwater is a critical resource worldwide and supplies approximately 30% of total freshwater to almost half of the world's population (Giordano, 2009; Aesbach-Hertig and Gleeson, 2012). It is commonly exploited under open access conditions, which often result in excessive pumping. Groundwater is especially important in California, where it regularly supplies more than half of all water consumption in drought years. Basins are depleted during those times, and pumping costs rise in response. Additionally, future water supplies are threatened when this drawdown continues without sufficient recharge in wet years. Rapid extraction also can lead to permanent losses in storage potential as subsurface geologic strata compact, with severe cases in Mexico City, Bangkok, Shanghai, and California's Central Valley (Konikow and Kendy, 2005). Meanwhile, seawater intrusion as a result of excessive pumping harms water quality, rendering it unfit for human consumption and agriculture. Intrusion has been documented in coastal areas from Oman to California (Zekri, 2008; Barlow and Reichard, 2010).

In California, the basic legal doctrine governing groundwater restricts the number of potential groundwater users and requires that groundwater use be "reasonable and beneficial." However, this restriction has been interpreted to include low-value agricultural uses, such as growing alfalfa in the desert. The result is *de facto* open access for landowners. Resource users have several options for restricting groundwater use, which vary in stringency. We focus in this paper on the most stringent and most difficult to implement: groundwater rights adjudication.

Adjudicating groundwater rights places a restriction on pumping, which constrains land owners' productive capacity; however, doing so ensures long-term resource availability for those still able to produce, grants a fungible asset that can be traded, and reduces uncertainty for residential developers. While the restriction may reduce agricultural rents initially, improvements in resource health make future resource access more certain. As expectations about resource access improve, the time horizon of rent generation increases. Where rights are tradable, future increases in the value of marginal water are capitalized into the price of rights. Access to water is typically associated with land parcel ownership, so parcels with better access or better rights should be worth more, and previous work suggests this link with land prices is observed in empirical data (Hornbeck and Keskin, 2014; Edwards, 2016; Buck et al., 2014).

B. Literature Review

Economists' understanding of groundwater resource management has evolved significantly over the past decades. Gisser and Sanchez (1980) present an early dynamic model of groundwater exploitation in a simple "bathtub" aquifer with homogeneous users. The main theoretical result is that marginal benefits of groundwater pumping should be equated with the sum of marginal extraction costs and the shadow value of leaving water in the aquifer for use in future periods. A sole owner follows this extraction path, while competitive extractors under open-access conditions ignore all or part of the shadow value of water because they are not the residual claimants to any water left in ground. This results in over-extraction under open-access conditions. However, under Gisser and Sanchez's model assumptions, the magnitude of this inefficiency is unlikely to be economically meaningful, leaving little room for groundwater management initiatives – this has been termed the "Gisser-Sanchez Effect" (GSE).

This result does not match reality on the ground. While many open-access groundwater aquifers remain in good health because exploitation is low, many are also overexploited, exhibiting falling water tables, increasing pumping costs, subsidence, seawater intrusion, and other negative effects. Aquifer drawdown may be efficient, especially during drought when surface water supplies are scarce, but these cases suggest that the costs of open access are not trivial. Indeed, agents in California and elsewhere have engaged in collective action to limit withdrawals, suggesting that potential gains exist.

Koundouri (2004) provides a useful overview of the conditions required for the GSE: that the aquifer is arbitrarily large, demand is linear, demand growth is not present, and quality or other externalities do not exist. These conditions do not usually hold. When the aquifer is small, wells are close enough that cross-well interference is an issue, demand growth is present, demand is nonlinear, or collateral impacts of drawdown are severe (such as with seawater intrusion or subsidence), the losses of open access may be large and of significant economic importance (Brozovic et al., 2010; Brill and Burness, 1994; Worthington et al., 1985; Zekri, 2008; Barlow and Reichard, 2010). These costs can be attenuated through adjudication of property rights, as a cap is set on total extractions and users subject to substantial collateral impacts of drawdown can contract with other users to reduce these impacts. Important for our work is that the total value of the resource increases as aggregate pumping is reduced from open-access levels; because water is a critical production input, this has implications for the value of agricultural land (Hornbeck and Keskin, 2014; Edwards, 2016; Buck et al., 2014; Yoo et al., 2013).

This is not the first paper to use a spatial regression discontinuity design (RD) to estimate the effect of institutions on land value. Grout et al. (2011) use a spatial RD to demonstrate that land values are affected by urban development boundaries in Portland, Oregon. More recently, Turner et al. (2014) identify own-lot, spillover, and scarcity effects of land use regulation using sophisticated spatial RD designs that estimate different effects at different distances from the boundary. These studies investigate the effect of institutions on the regulated item itself: land. In contrast, we follow the literature suggesting that institutions that alter the ability to access groundwater have implications for land values and use land prices as an indicator of the value of increased groundwater reliability. Because groundwater levels do not change discontinuously at the border, we do not identify the total effect of adjudication but rather the effect of being in a regulated area (which we describe in the next section). Nonetheless, the fundamental approach and assumptions of our empirical strategy are similar to those in the literature.

III. Conceptual Model

We present a model of how land prices are expected to vary across our discontinuity threshold. Following Cappozza and Helsley (1989, 1990) we assume the land price for any undeveloped parcel capitalizes the present value of expected land rents. This rent is made up of two components: the agricultural rent potential of the land and the value of future rent increases due to urban growth, should the parcel eventually be developed. However, because our discontinuity is located quite far from urban areas and development pressure is unlikely to change discontinuously at the boundary, we focus here on the effects of groundwater adjudication on agricultural rent generation and ignore effects on the likelihood of development. To this we add the wealth associated with pumping permits because it is capitalized into land value (how the data capture this is described in more detail in Section IV). Because these permits have value to both agricultural pumpers and municipal water utilities, development pressure still plays a role in the market price of groundwater pumping rights and thus land value.

Groundwater adjudication defines volumetric pumping rights (as shares of a total safe yield) based on historical use, allocates them to groundwater users within the adjudicated area, and allows for a trading market. Groundwater rights are then ramped down until the basin is brought into balance, i.e., long-term groundwater levels are stabilized. Any user overlying the aquifer but outside of the adjudicated area that can drill a well is effectively unrestricted in pumping, as before adjudication.

We extend the groundwater pumping model presented by Edwards (2016). In the first subsection, we illustrate how adjudication results in relatively higher agricultural rents for a free rider outside the adjudicated area and then show that the allocation of free pumping permits to adjudicated groundwater users increases firm value. In the following section, the optimal management of rights in the face of exogenous urban growth is characterized and an expression for the spatial regression discontinuity treatment effect is formulated.

A. *A Model of Open-Access Pumping and Groundwater Property Rights*

A groundwater user i maximizes his or her utility at time t, $\pi\left(w_i(t), h_i(t)\right)$, from pumping groundwater subject to an equation of motion describing recharge and the movement of groundwater. Water pumped is represented by $w_i(t)$ and the contemporaneous water table height is $h_i(t)$. The dynamic optimization problem is:

$$\begin{aligned} V_i^0 &= \max_{w_i} \int_0^\infty \pi\left(w_i(t), h_i(t)\right) e^{-\delta t}\, dt \\ s.t\; \dot{h} &= r - w_i(t) - \theta\left(h_i(t) - h_{-i}(t)\right) \end{aligned} \tag{1}$$

Throughout time, net benefits of water use are discounted by a rate δ. Meanwhile, local water table elevation, $h_i(t)$, gains local recharge, r, and loses water extracted by the user as well as the water that flows away from or toward i. For simplicity in this case,

$h_{-i}(t)$ represents the average water level of surrounding parcels. If $h_{-i}(t) > h_i(t)$, i is a net recipient of water and inflow increases local water table elevation. We assume a constant local recharge rate, r, because along the adjudication boundary recharge is unlikely to vary.

The subterranean flow of water is regulated by $\theta = \frac{k}{d}$, where k represents hydraulic conductivity and d the distance between parcels. The optimal steady-state pumping pathway under open access is determined by the following condition:

$$\frac{\partial \pi}{\partial w_i} = \frac{1}{\delta}\left(\frac{\partial \pi}{\partial h_i} - \frac{\partial \pi_i}{\partial w_i} \cdot \theta\right). \tag{2}$$

The first coefficient is the inverse of the discount rate, making this a perpetuity value. The pumper extracts groundwater until the marginal benefit of doing so equals the discounted cost of lower water tables in the future attenuated by the value of additional water that flows towards (or doesn't flow away from) user i, which is regulated by θ. In cases of basin overdraft, $\sum_{i=1}^{n} w_i > n * r$ such that water tables fall in aggregate until increasing pumping costs force all users to reduce pumping such that $\sum_{i=1}^{n} w_i = n * r$ and the basin is in balance. This may occur when the aquifer storage is depleted.[4] This results in a constant water table at $h^{¿}$ and zero marginal profits because the resource is overutilized.

Now suppose that all or most users agree to adjudicate and restrict pumping. They define annual pumping rights, $A_i(t)$, and restrict those rights such that in each period

$\sum_{i=1}^{n} A_i = n * r$ and water levels stabilize. However, stabilization is achieved at a higher water table level than results under open access, $\acute{h} > h^{¿}$. When this higher water table is maintained, the marginal net return to each unit of pumping in equilibrium is higher than under open access, so positive rents accrue to resource users. Although resource users lose out in the short term because less water can be pumped, higher water levels in the long term ensure a stream of profits greater than those realized under open access. For adjudication to enhance welfare, discount rates must be low enough that the long-term benefits outweigh short-term costs. We now illustrate how unregulated and regulated users exploit these benefits differently.

When users overlie the aquifer but are not subject to property right restrictions, such as free riders on the fringe of the resource, their agricultural rents increase following adjudication more than those of adjudicated parties. To see this, consider that a free rider faces an exogenous neighboring water table height of $\acute{h}$:[5]

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4 We assume for now that all users are homogeneous so that pumping is reduced for all and no users exit or stop pumping altogether.

5 We assume for simplicity that in aggregate the free riders do not affect aggregate water levels within the adjudication; relaxing this assumption requires the interior users to restrict pumping even further to make up for drainage out of the adjudicated area but adds little to the analysis.

$$V_i^{FR} = \max_{w_i(t)} \int_0^{\infty} \pi\left(w_i(t), h_i(t)\right) e^{-\delta t} dt$$

$$s.t\ \acute{h} = r - w_i(t) - \theta\left(h_i(t) - \acute{h}_{-i}(t)\right). \tag{3}$$

Because $\acute{h} > h^{¿}$, the free rider can drain water more easily from within the adjudicated area compared to under open access conditions, effectively increasing recharge. This increased drainage from neighbors results in a higher rate of profitable steady-state pumping. The free rider does not face a constraint on pumping and can siphon off water left in the ground within the adjudicated area, increasing private net benefits and forming a gradient of groundwater flow towards the exterior of the aquifer. The excess rents that can be earned by a free rider in steady state are derived from this increased inflow, which scales with $\theta = \frac{k}{d}$. We denote this steady-state pumping rate $w_i^{¿*¿}$.

In contrast, the adjudicated users are restricted. The number of rights held, $A_i(t)$, allows a user to pump $w_i(t) = A_i(t)$ units of water at each point in time. Define the number of permits purchased (or sold) by any user in time t as the amount of pumping in excess of (or below) currently held rights, $z_i(t) = w_i(t) - A_i(t)$. Pumping can exceed initial allocation for the unit price of a volumetric pumping right, γ, leased at that point in time. An additional restriction must be imposed that some finite amount of basin overdraft, D, is permitted as rights are ramped down (proportionally) to their long-term levels, $\acute{A}_i$, at some time t^{Eq} to bring the basin into balance. This results in the following dynamic optimization problem for cooperative users:

$$V_i^{AD} = \max_{w_i(t)} \int_0^{\infty} [\pi(w_i(t), h_i(t)) - \gamma(w_i(t) - A_i(t))] e^{-\delta t} dt$$

$$s.t\, \acute{h} = r - w_i(t) - \theta(h_i(t) - h_{-i}(t)), \qquad (4)$$

$$\int_0^{t^{Eq}} \sum_{i=1}^{n} w_i(t) - r\, dt = D.$$

If balance is imposed immediately, $D=0$ and $A_i(t) = \acute{A}_i \forall t$. In this case, users exploit groundwater according to the following rule, where the market price of a right is determined by the intersection of a static demand curve with an entirely inelastic supply curve based on the amount of total annual allowable pumping:

$$\frac{\partial \pi}{\partial w_i} = \frac{1}{\delta}\left[\frac{\partial \pi}{\partial h_i} + \theta\left(\gamma - \frac{\partial \pi}{\partial w_i}\right)\right] + \gamma. \qquad (5)$$

The amount of steady-state pumping for an adjudicated user, $w_i^{¿}$, decreases with γ because pumping takes on a new opportunity cost: that of selling permits.[6] If $\gamma > \frac{\partial \pi}{\partial w_i}$, the pumper is better off restricting pumping in order to sell the permit. In the absence of temporal

6 A higher right-hand side implies lower pumping due to the concavity of the profit function with respect to pumping.

shocks, users transact permits following adjudication and equilibrium pumping and profits are maintained in perpetuity.

B. Optimal Sale of Rights and the Determinants of Land Value

The absence of any temporal changes is a strong assumption. One option to relax this assumption is to consider the optimal number of rights to hold in the face of population growth that drives up urban water demand (and also the price of permits because supply is fixed at each point in time). When the opportunity cost of permits grows in the future, rights holders may cease producing crops at some point and sell their rights. Because water rights themselves are an asset, the price of which capitalizes the highest of all future possible rental streams, this has important implications for the value of the water rights held on a parcel. We derive here the optimal time of sale for water rights and incorporate this into an expression for land value.

In particular, the price of permits is now assumed to be $\gamma(t)$ and $\acute{\gamma} > 0$. To simplify matters, we also assume here that a user purchases a discrete bundle of water rights, w_{0i}, and sells them at one point, $t^{¿}$, in the future. The order of events is as follows: 1) property rights are defined and allocated, 2) users transact rights to reach equilibrium in $t = 0$, and 3) each user produces crops until $t_i^{¿}$, when the bundle is sold to the municipality. Suppressing subscripts for simplicity, a representative user solves:

$$\max_{w_0, t^{¿}} \int_0^{t^{¿}} \pi(w_0 \vee \acute{L}) e^{-\delta\tau} d\tau - \gamma(0) ¿ w (¿¿ 0 - A(0)) + \int_{t^{¿}}^{\infty} \gamma(\tau) w_0 e^{-\delta\tau} d\tau. \qquad (6)$$

The final term can be thought of as the salvage value of the water rights. The user chooses the optimal bundle of rights, $w_0^{¿}$, subject to condition (5)[7], for fixed land $\acute{L}$, and including the future salvage value of any right purchased in $t=0$. The bundle of rights is sold when the instantaneous returns to agriculture equal the rent in urban uses:

$$\pi(w_0^{¿}) = \gamma(t^{¿}) w_0^{¿}.$$

One implication of this derivation is that the value of land with water rights varies with t because the value of future increases is discounted less with time. The following expression defines land values inside the adjudicated area at the boundary:

$$V^{Land,Adj}(t) = \int_t^{t^{¿}} \pi(w_0^{¿}, h^b) e^{-\delta(\tau-t)} d\tau + \frac{\gamma(t^{¿})}{\delta} e^{-\delta(t^{¿}-t)} w_0^{¿} + \frac{1}{\delta} \int_{t^{¿}}^{\infty} \gamma'(\tau) w_0^{¿} e^{-\delta(\tau-t)} d\tau + \int_{t^{¿}}^{\infty} \rho e^{-\delta(\tau-} \qquad (7)$$

At the boundary, water tables are held constant in time at $h^b \leq \acute{h}$, which may be lower than water tables in the interior due to the gradient induced by free riding. The first term in (7) captures agricultural rent until $t^{¿}$; the second two separate the value of water rights into the present value of 1) the stream of their value in the agricultural application at time $t^{¿}$ and 2)

7 We abstract in this formulation from the water table height because the adjudication holds it fixed in time as well as any local drawdown effects, consideration of which is implicit in the choice of $w_0^{¿}$.

the present value of the stream of all future increases in value; and the final term represents the perpetuity of land value in non-agricultural uses, $\rho < \pi\left(w_0^{¿}, h^b\right)$, after rights are sold. In contrast, free riders cannot trade rights to any water used on their property, so land value is invariant to time and can be expressed at the boundary simply as:

$$
\begin{array}{l}
¿*¿, h^b \\
w^{¿} \\
¿ \\
\pi ¿ \\
V^{Land,FR} = ¿
\end{array}
\quad (8)
$$

Combining (7) and (8), an expression for the effect identified by the spatial regression discontinuity can be written. In particular, we subtract the value of a free riding parcel from that of a parcel owned by a cooperative user, where the characteristics of the owners are considered to be held constant:

$V^{Adj} - V^{FR}(t) = ¿$

$$¿*¿, h^b$$
$$w^{¿}$$
$$\pi\left(w_0^{¿}, h^b\right)\left(1 - e^{-\delta\left(t^{¿}-t\right)}\right) + \rho e^{-\delta\left(t^{¿}-t\right)} - \pi ¿.$$
$$\left[\frac{\gamma\left(t^{¿}\right)}{\delta} e^{-\delta\left(t^{¿}-t\right)} w_0^{¿} + \frac{1}{\delta}\int_{t^{¿}}^{\infty} \gamma'(\tau) w_0^{¿} e^{-\delta(\tau - t)} d\tau\right] + \frac{1}{\delta} ¿ \quad (9)$$

The first bracketed term encapsulates the total value of volumetric water rights held on the interior, and the second represents the difference in the present value of potential agricultural rents (or other land uses), which is strictly negative because $¿*¿, h^b$ $w^{¿}$ $¿$ $\pi ¿$. Whether adjudicated parcels will be worth more than unadjudicated parcels on the fringe of the resource depends on the relative magnitude of two effects described here. First, a small number of unadjudicated users will be able to generate higher agricultural rents in steady state because they can siphon off water effectively from the adjudicated area, increasing the amount of water that can be pumped at profit. The interior group restricts pumping for its own benefit, but unrestricted free riders can exploit this benefit aggressively. On the other hand, interior users are granted pumping allowances that are tradable. When the returns to water use elsewhere are sufficiently large, users with adjudicated rights can trade them away at profit (free riders do not have this opportunity). In cases where permit prices grow over time due to increasing demand, such as the expansion of developed urban areas this wealth effect can be quite large.

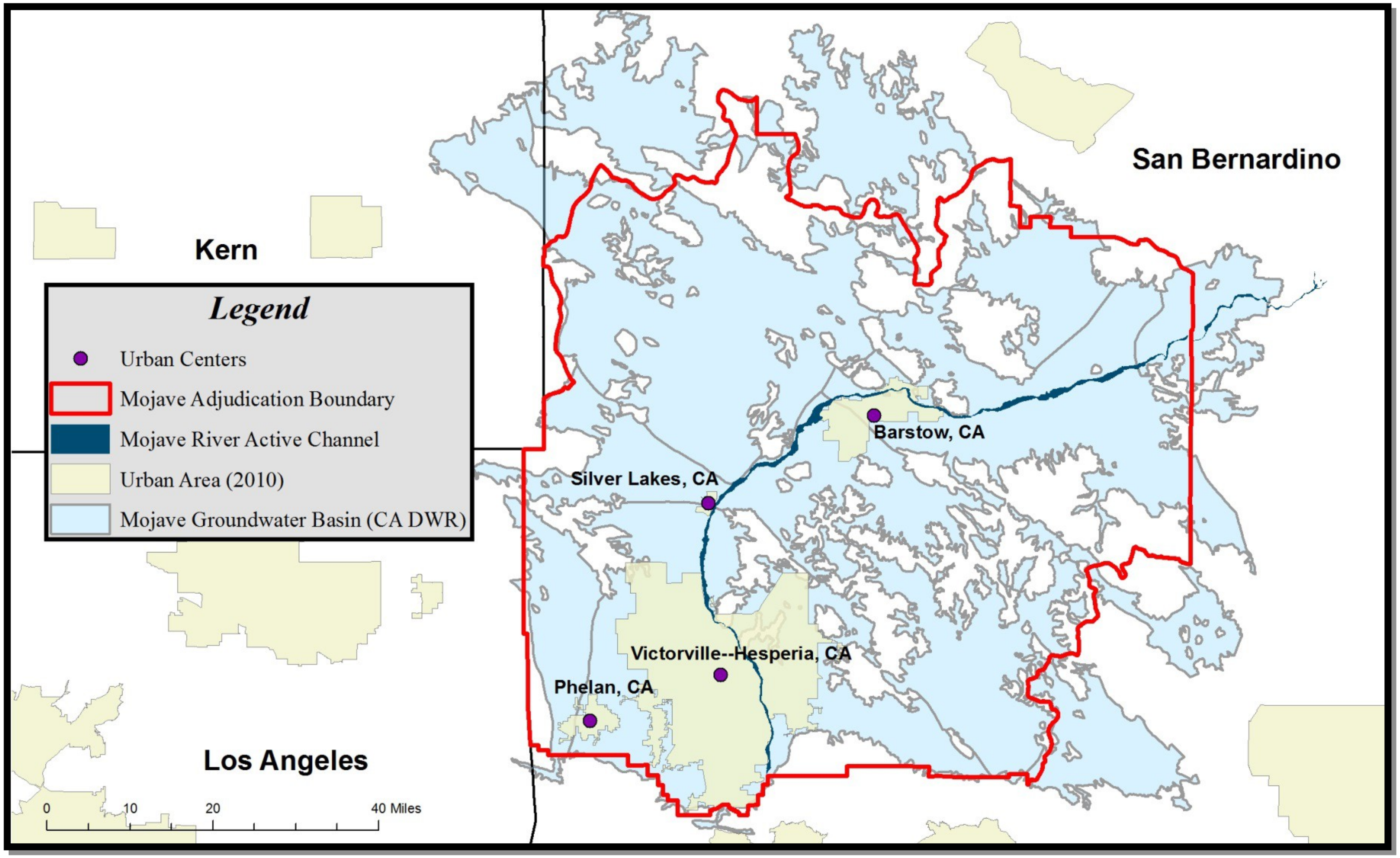
A spatial regression discontinuity empirical approach based on the adjudication boundary will subtract the average value of untreated parcels at the boundary from that of treated parcels. This allows us to identify the empirical analog of the expression above, which does not include the direct effect of higher groundwater tables on the value of land because both treated and untreated parcels experience this. Thus, it represents a lower bound on the effect of adjudication. In our empirical framework, stipulating to an adjudication decision increases land value relative to free riders when the capitalized present value of groundwater pumping permits exceeds the agricultural rent premium enjoyed by free riders. Three main points result:

1) The overall sign of the expression will be positive if the first bracketed term, representing the value of capitalized water rights, dominates the second, which represents the gains to free riding and is negative.
2) With homogeneous agents, the magnitude of the estimated coefficient represents a lower bound on the effect of adjudication on treated parcels. Because θ is decreasing in distance between pumpers and the regression discontinuity coefficient recovers the effect as distance goes to zero in the limit, drainage losses to free riders are at their largest at the boundary. In other words, free riders gain less and cooperators gain more at greater distances from the boundary.
3) Where demand for permits grows quickly (such as in areas with growing urban centers) or hydraulic conductivity is low, the effect should be larger.

IV. Data and Empirical Setting

Our study area is the Mojave River Groundwater Basin, located in southern California in San Bernardino County. Approximately 95% of the water resources in this area originate from the Mojave River; the river experiences surface flow only rarely, during large storm events. Most water for human uses is acquired through pumping groundwater, which is recharged by precipitation and the eventual percolation of river flow. As a result, groundwater is a critical resource for both agriculture and urban development (drinking water). Although over-extraction

Figure 1: Map of Study Area



Caption: The Mojave River groundwater basin in southern California. The Mojave River flows from mountains in the south through the desert to the northeast. Victorville, Hesperia, and Barstow are the largest and most quickly growing urban areas. We restrict ourselves to sections of the boundary found in San Bernardino County to avoid the confounding influence of boundaries with Kern and Los Angeles counties.

has led to ground subsidence and drying and cracking of the land surface, restricting pumping mainly returns resource benefits by reducing pumping costs and ensuring long-term access. The study area is detailed in Figure 1 on page 17.

The Mojave River groundwater basin was adjudicated between 1990 and 1996 after a failed earlier attempt to reach agreement in the 1960s. Volumetric pumping rights were defined as a proportion of an aggregate annual pumping yield. Each user's proportion equals his or her proportion of total pumping, on average, in the five years preceding adjudication. This total yield was initially set at historical levels, and the rights are designed to be ramped down until basin balance is achieved (i.e., water tables are stabilized in the long run). Rights are tradable; however, the adjudicated area is split into five primary subareas, and rights can only be traded within the subarea in which they were allocated. These subareas will play a role in structuring our empirical analysis because differing permit demand across subareas may explain heterogeneous treatment effects.[8]

Leasing of groundwater pumping rights is common in the Mojave, while sales of permanent rights are rarer. The average lease price is ~$250/acre-foot, and sale prices vary substantially between subareas, from $2,000/acre-foot to $4,000/acre-foot (Donohew, 2005). While leasing demand is made up of agricultural and urban users, permanent sales often involve agricultural users selling rights in perpetuity to growing urban areas.[9] This is spurred in large part by growing urban demand; for example, between 2000 and 2010 the population of Victorville

8 Subarea boundaries were drawn to reflect physical (hydrogeologic) features. Although the entire aquifer is connected, some areas share higher hydraulic conductivity than others and were lumped together into a subarea.

9 Personal communication with Tony Winkel, Senior Hydrologist, Mojave Water Agency. 8 February 2017.

almost doubled (~64,000 inhabitants vs. ~115,000 inhabitants).[10] Hesperia and Barstow have also grown substantially. Rapid urban growth suggests the wealth effect may be substantial.

Data on assessed land values for agricultural and vacant land parcels were collected from the San Bernardino County Assessor. Assessed land values are constructed on the basis of local land sales and updated annually to keep pace with inflation and market conditions. The assessor explicitly considers access to groundwater resources, especially for agricultural or vacant land parcels. An important note is that the assessment procedure for land does not explicitly account for adjudication. No additional term is added to the assessor's land value prediction model to account for adjudication, so our estimation does not simply recover a parameter from the assessor's model.[11] Because the assessor's model uses only local comparable sales prices, we estimate differences that result from different parcel sales prices on either side of the boundary. Although a pumping right can be severed from the land, severance does not occur until a permanent transfer is undertaken; before that, the value of adjudicated pumping rights is included in the parcel value. Furthermore, if a water right is transferred to another parcel, the assessor uses the market transaction price to value the water right before including it in the assessed value of the new land parcel.[12] Only if a severed right is sold to a municipal water agency is its value no longer directly reflected in the land values on the assessor roll. Incidentally, water right value may also be missing from our analysis if a right is severed and transferred to another parcel that is not within the buffer we choose for our regression discontinuity. Still, we are not especially concerned with the possibility of missing rights because permanent transfers are relatively rare: the average number of permanent pumping right sales in any year is less than one percent of the

10 U.S. Census figures.

11 Personal communication with San Bernardino County Assessor and Recorder's Office. 20 July 2017.

12 *Idem.*

total cap, and most such transactions take place in the Alto subarea, which we omit from our analysis (Donohew, 2005).

Assessed land value data reflect market transaction prices, but they are nonetheless imputed and may not accurately reflect true market value. Land value assessors update land values at the time of sale but thereafter model market prices using observed local transactions and taking relevant factors into account. Ma and Swinton (2012) investigate the usefulness of assessed land value data for hedonic studies of agricultural land using data from Michigan. In comparing assessed and transaction data, they focus on the contribution of local environmental amenities and find that assessor data does not do a good job of capturing those values in exurbanizing areas; however, their empirical results suggest that assessed values do a very good job of capturing the contribution of agricultural productive potential, which is the focus of our task. We follow other recent work in using assessed land value data as well; for example, Bigelow et al. (2017) find that assessed values in Oregon serve as a good proxy for true land value.

Along with value, we also possess measures of parcel area, the base year of appraisal,[13] distance to an urban center, the effect of local groundwater recharge sites operated by the MWA, and the average slope of each land parcel, which is an important determinant of agricultural potential. Distance to an urban center and terrain slope are calculated using shapefiles from the Federal Highway Administration (urban areas) and digital elevation maps from USGS, respectively. Finally, we follow our analytic model and take the sum of the inverse distance to

13 The base year of appraisal or assessment matters because it represents the point in time at which the real value of the property was either observed in a market transaction or estimated on the basis of comparable nearby parcels by the assessor's office (in the event the parcel was not transacted but rather built upon or otherwise substantially altered). While the assessor has some leeway to change a parcel's assessed value aside from adjusting for inflation, California statutes do not allow the assessor to apply a rate of increase greater than 2% annually. Thus, base year of appraisal may be influential in explaining observed land values.

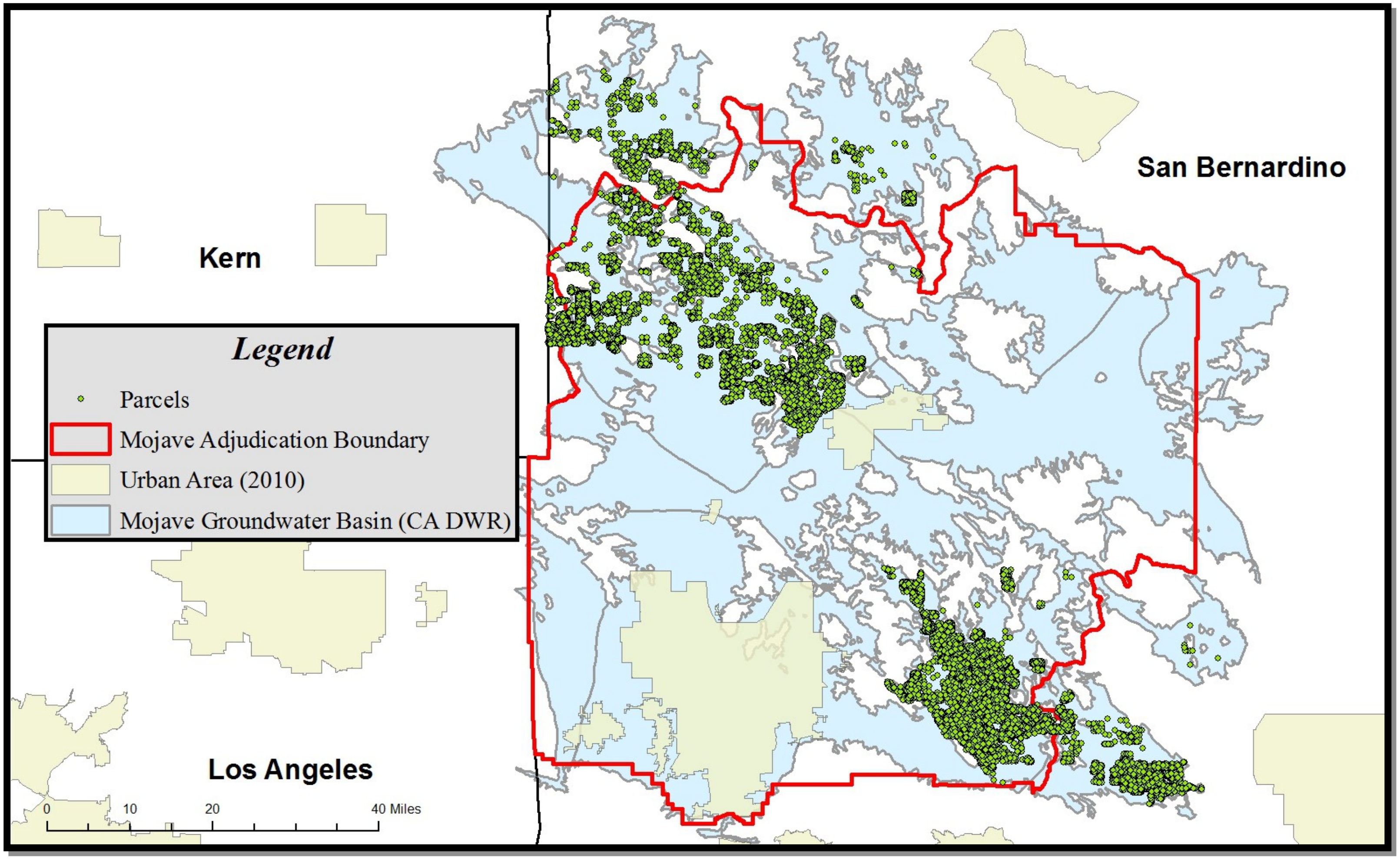
each recharge site as a measure of the effect of recharge, thereby assuming equal recharge from each site. The distance to the adjudication boundary is the shortest straight-line distance from a parcel's centroid to the adjudication boundary.

We pare down the sample significantly. First, we remove all urban parcels. Second, we omit parcels in Kern and Los Angeles counties because the adjudication boundary overlies the county line exactly, which would confound inference. In addition, we omit parcels with missing data and those owned by government or government-associated entities. Finally, parcels not in the Northwest (Centro) or Southeast (Este) Subareas of the adjudicated area are removed. The Alto and Oeste Subareas are removed from the southwest because they contain numerous urban parcels, parcels on the urban fringe, and parcels in the adjudicated area with no nearby partner parcels on the exterior. Observations from the Baja Subarea in the northeast are removed because topography and patterns of government land ownership inhibit continuity in the running variable, invalidating the RD approach (see Figure 6(d) in Appendix, B). The final sample of 14,366 observations is shown in Figure 2 on page 22.

In general, identifying the effect of groundwater adjudication on land value is difficult due to endogeneity concerns. A simple cross-sectional analysis across basins is problematic because treatment is not randomly assigned; basins with higher land values may be more likely to adjudicate to protect resource access, or other unobserved basin characteristics may affect both the likelihood of adjudication and the level of land values (for example, being near a coastline). Because we have parcel-level data on assessed land values, we are able to exploit discontinuity in the boundary of the adjudicated area to achieve identification.

However, there are several major considerations. If the boundary of the adjudicated area aligns with the boundary of the aquifer, identification is confounded by the effect of having

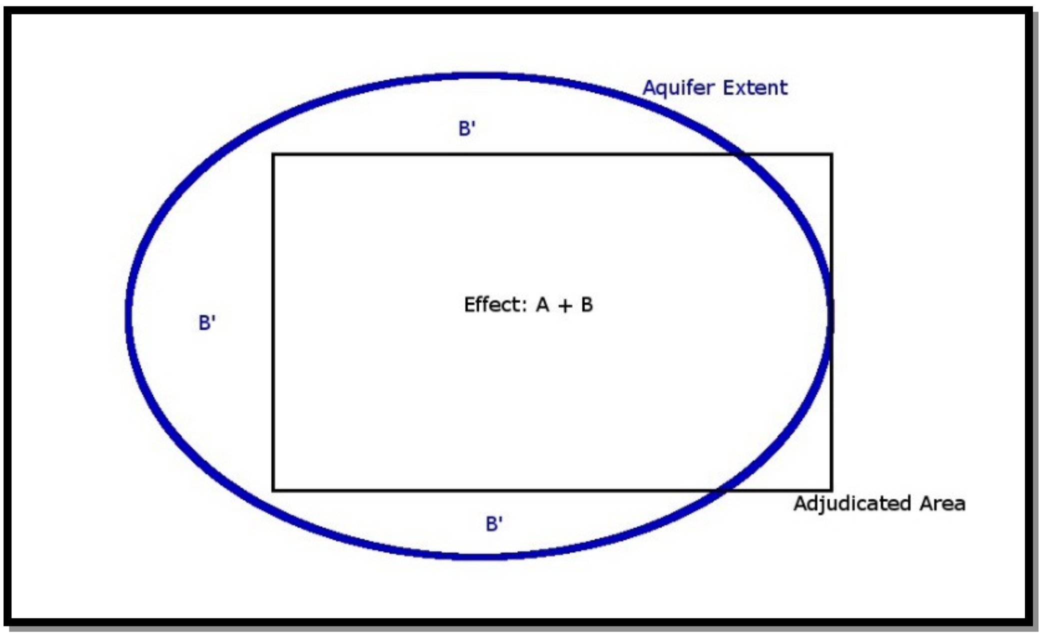
Figure 2: Study Sample



Caption: The sample presented here consists of 14,366 parcels. We remove any parcels located within urban areas as well as any not overlying the aquifer. We also only include parcels in the northwest (Centro) and southeast (Este) subareas. Parcels cluster within subarea boundaries.

groundwater access at all; we must find sections of the adjudication boundary that overlie the aquifer, separating unadjudicated (open access) parcels overlying the aquifer from adjudicated parcels overlying the aquifer. Second, because higher groundwater table levels spill over the boundary to unadjudicated parcels, we define two different resource endowment effects. Third, the regression discontinuity design is challenged in this case: because not all users received grandfathered rights or hold rights today, the effect at the boundary will be highly heterogeneous and potentially difficult to identify. This heterogeneity could contribute to large standard errors and will complicate interpretation of the average effect for a representative parcel.

Figure 3: Identification Mechanics



Caption: Various effects of adjudication on land value.

Our identification strategy is summarized in Figure 3. In this diagram, A represents one effect of being adjudicated: the possession of a guaranteed right to pump groundwater that can be traded. The effects on agricultural productivity, reflected in land value, are denoted with the letter B. Higher water levels created by adjudication are enjoyed by all users, but free riders and cooperators exploit the resource endowment effect differently due to the lack of pumping restrictions outside the boundary. Therefore, B is defined as the effect for adjudicated parcels and $B^{'} > B$ as the effect for parcels outside the boundary. Through our spatial RD we identify the difference in land value between parcels inside and outside the adjudication boundary: $(A+B) - B^{'} = A + (B - B^{'})$. A positive value will be recovered when the present value of allocated permits, A, exceeds the agricultural rent premium enjoyed by free riders, $(B^{'} - B) = -(B - B^{'})$, as described in Section III.

The assumptions required for identification of general regression discontinuity designs are summarized by Lee and Lemieux (2010). The most important in our case is that agents cannot sort themselves across the boundary (i.e., it is exogenous): if they cannot, then treatment randomization is ensured and observational units on either side of the discontinuity should be proper counterfactuals for one another. In this case, the average treatment effect is estimated. One way to assess whether this assumption holds is to test whether relevant covariates develop smoothly across the boundary.[14]

Our discontinuity of interest is the edge of the adjudication boundary. It was set as the intersection of the boundary of the surface water drainage area for the Mojave River and the boundaries of the Mojave Water Agency (MWA), the third-party watermaster appointed to enforce the judgement. Parcels in the analysis lie above the aquifer but are treated based on their location relative to the boundary defined above. Because the MWA was formed several decades

14 In contrast, a typical matching approach would simply test whether covariates are balanced – in this case, we can allow for imbalanced covariate means because so long as the difference at the boundary is smooth, identification is not threatened. Another option is the McCrary test, which we report in the Results Appendix, B.

prior to adjudication for different reasons, individual parcels could not sort themselves across the boundary at the time of adjudication, so we do not suspect manipulation of treatment status on the part of landowners. In particular, the boundaries of the MWA were drawn to include parcels that would finance State Water Project (SWP) infrastructure, which was not connected until decades later; SWP water is used to recharge groundwater, so no discontinuity in SWP access exists. The definition of groundwater rights played no role in the formation of the boundary.

V. Results

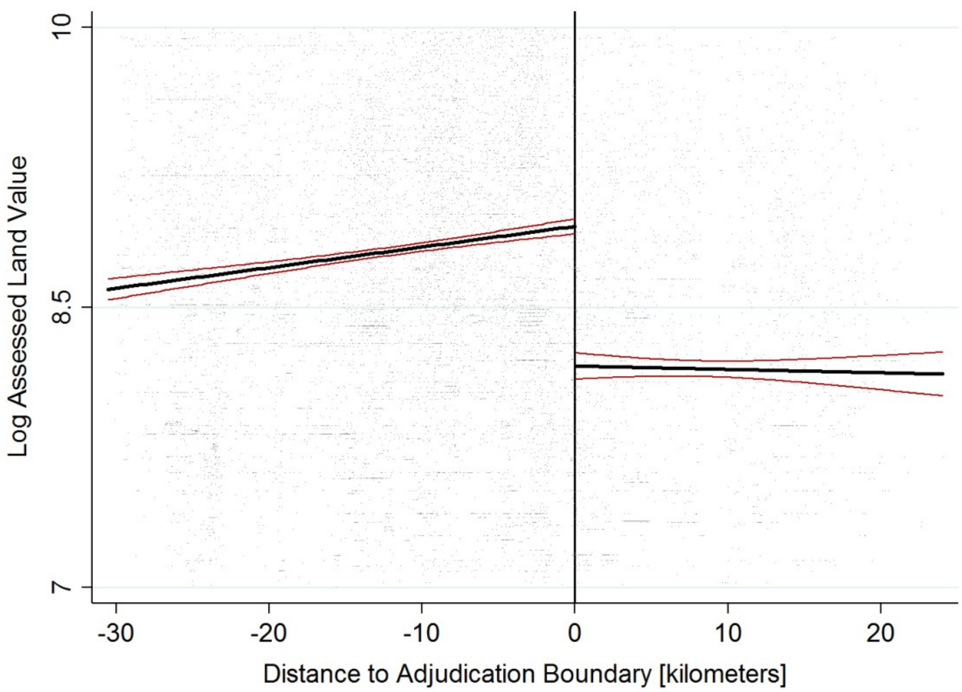
We first present results using the entire sample and then present segment-specific estimates to uncover any spatial heterogeneity in the treatment effect. The dependent variable is log land value for each parcel. Our regression specification takes the following form, typical of other spatial RD designs:

$$\ln(Value_i) = \beta_0 + \beta_1 Distance_i + \beta_2 Distance_i * Adj_i + \beta_3 Adj_i + \beta_4 X_i + \varepsilon_i , \qquad (7)$$

in which the treatment effect of interest is identified by β_3 and we allow land value to vary with the forcing variable, distance to the boundary, differently on either side. Including relevant covariates, X_i, can help to reduce variance in the identification of the treatment effect, control for any changes at the boundary (should they exist), and correct for imbalance across the treated and control samples (Lee and Lemieux, 2010), so we present selected specifications with parcel area, distance to nearest urban center, the base year of assessment, our measure of recharge, average terrain slope, and in some cases latitude and longitude. In all specifications, standard errors are corrected for potential heteroscedasticity and spatial autocorrelation using uniform kernels (code from Hsiang, 2010).

First, we illustrate the effect of adjudication semi-parametrically using linear functions in Figure 4. Distance values above zero correspond to parcels outside the adjudicated area. As this figure presents raw data, the slopes do not track the effect of groundwater access. The gap in land values at the boundary is the effect of interest. Confidence intervals suggest a significant jump across the adjudication boundary, which we test more rigorously using local linear regression, with results in Table 1 on page 27.

Figure 4: Relationship between Distance to Boundary and Log Land Value



Caption: Visual representation of log land value data, with boundary location in red. Plot is truncated at log values of 7 and 10 for ease of viewing.

We use algorithms designed by Calonico et al. (2014) (CCT) and Imbens and Kalyanaraman (2012) (IK) that attempt to address the bias-precision tradeoff inherent in regression discontinuity designs.[15] In Table 1, linear polynomial bandwidths are 5.2 and 3.9 kilometers on either side of the boundary using CCT and IK bandwidths, respectively. Alternating columns include control covariates.

Table 1: Spatial RD Results

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Log LV	Log LV	Log LV	Log LV	Log LV	Log LV	Log LV	Log LV
Adjudication Dummy	0.372	0.479**	0.376	0.423**	0.439	0.570**	0.465	0.577**
	(0.276)	(0.196)	(0.297)	(0.202)	(0.308)	(0.239)	(0.306)	(0.240)
Boundary Distance	-0.115	-0.228***	-0.182	-0.276**	-0.118	-0.305	-0.122	-0.298
	(0.0816)	(0.0728)	(0.118)	(0.124)	(0.210)	(0.240)	(0.215)	(0.246)
Distance*Adjudicated	0.274***	0.419***	0.386**	0.507***	0.00434	-0.0127	0.00347	-0.0116
	(0.104)	(0.0881)	(0.154)	(0.141)	(0.0320)	(0.0363)	(0.0339)	(0.0382)
Distance^2					0.228	0.461	0.205	0.437
					(0.294)	(0.293)	(0.302)	(0.302)
Distance^2*Adjudicated					0.00564	0.0197	0.0120	0.0220
					(0.0347)	(0.0382)	(0.0367)	(0.0404)
Covariate Controls								
Parcel Area		0.0130***		0.0130***		0.0136***		0.0134***
		(0.00166)		(0.00186)		(0.00169)		(0.00167)
Base Year		-1.31e-05		1.50e-05		-1.87e-05		-1.98e-05
		(2.92e-05)		(3.38e-05)		(2.77e-05)		(2.82e-05)
Distance to Urban Center		-0.0183**		-0.00506		-0.020***		-0.0184**
		(0.00882)		(0.0116)		(0.00750)		(0.00777)
Recharge Effect		-5.670		0.348		-5.358		-5.106
		(6.213)		(7.376)		(5.438)		(5.606)
Average Slope		0.0131		0.0145		0.0164		0.0118
		(0.0108)		(0.0113)		(0.0110)		(0.0106)
Latitude		-0.979**		-0.700		-1.091***		-1.092***
		(0.436)		(0.633)		(0.412)		(0.408)
Longitude		-1.363***		-1.298**		-1.428***		-1.401***
		(0.453)		(0.553)		(0.449)		(0.447)
Constant	7.865***	-116.5***	7.783***	-120.2**	7.841***	-120.3***	7.839***	-117.2***
	(0.242)	(44.65)	(0.266)	(49.53)	(0.284)	(44.69)	(0.284)	(44.69)
Observations	4,005	4,005	3,028	3,028	4,537	4,537	4,429	4,429
Bandwidth	CCT(5.2km)	CCT	IK(3.9km)	IK	CCT(6.2km)	CCT	IK(5.9km)	IK
Kernel	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform

15 As the bandwidth expands (i.e., more parcels are drawn into the analysis from a farther distance), more observations allow for the effect to be estimated with greater precision, but bias potentially increases as parcels farther away are included.

Covariates	None	Yes	None	Yes	None	Yes	None	Yes

Standard errors in parentheses and corrected for heteroscedasticity and spatial autocorrelation, and significance as follows: *** p<0.01, ** p<0.05, * p<0.1. Columns present optimal bandwidths according to CCT and IK algorithms, alternating inclusion of covariates.

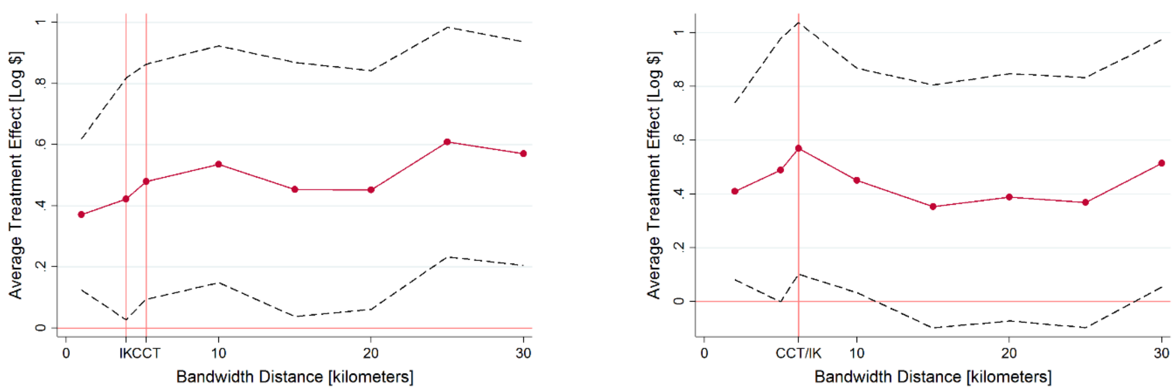
Table 2: Covariate Smoothness Tests

	(1) Parcel Area	(2) Base Year	(3) Urban Dist	(4) Agg Recharge	(5) Avg Slope	(6) Parcel Area	(7) Base Year	(8) Urban Dist	(9) Agg Recharge	(10) Avg Slope
Adjudication Dummy	3.988	-64.20	4.610	-0.00808	-0.240	7.683*	-31.04	3.422	-0.00319	-0.119
	(3.918)	(71.80)	(3.044)	(0.00601)	(0.289)	(4.456)	(77.30)	(3.307)	(0.00622)	(0.307)
Boundary Distance	-2.276	-3.567	-0.674	0.00395**	0.0927	-2.772	28.83	-1.004	0.00436*	0.0736
	(1.705)	(17.47)	(1.201)	(0.00183)	(0.0604)	(2.025)	(31.32)	(1.510)	(0.00245)	(0.0974)
Distance*Adjudicated	2.341	10.02	-1.146	0.00172	-0.0538	1.106	-65.29*	0.0171	-0.00161	-0.0929
	(1.925)	(22.92)	(1.377)	(0.00243)	(0.0943)	(2.597)	(39.41)	(1.854)	(0.00334)	(0.153)
Constant	6.323**	1,576***	33.43***	0.174***	1.693***	5.785*	1,617***	33.10***	0.174***	1.670***
	(2.920)	(51.31)	(2.366)	(0.00352)	(0.221)	(2.969)	(59.42)	(2.632)	(0.00396)	(0.241)
Observations	4,005	4,005	4,005	4,005	4,005	3,028	3,028	3,028	3,028	3,028
Bandwidth	CCT(5.2km)	CCT	CCT	CCT	CCT	IK(5.9km)	IK	IK	IK	IK
Kernel	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform

Standard errors in parentheses and corrected for heteroscedasticity and spatial autocorrelation, and significance as follows: *** p<0.01, ** p<0.05, * p<0.1. Columns (1)-(5) present covariate results for CCT bandwidth, (6)-(10) for IK.

The first row of Table 1 reports the coefficient of interest, and it is positive but generally not significant unless control covariates are included to decrease standard error estimates. Quadratic specifications support the results using linear specifications, with slightly increased magnitudes.[16] That the result is generally robust to bandwidth selection and the inclusion of covariates lends confidence to our interpretation that the adjudication boundary represents a relevant discontinuity. In Figure 5 the average treatment effect estimates are plotted against bandwidth, with CCT and IK bandwidths marked by vertical lines. The left- most estimate plotted in Figure 5 lies at the smallest bandwidth for which enough observations remained to credibly estimate the regression discontinuity model with control covariates. Estimate magnitudes attenuate slightly as we shorten the RD bandwidth, but they remain significant and economically meaningful. Within one kilometer (and even five kilometers), the likelihood of spatially dependent bias is small.

Figure 5: ATE Estimates by Bandwidth – All Segments



(a) Linear Polynomial **(b) Quadratic Polynomial**

Caption: Average Treatment Effect coefficients from regression discontinuity plotted against bandwidth chosen, including covariate controls. Vertical lines correspond to CCT and IK bandwidths, and 95% confidence intervals are shown in dashes. CCT and IK bandwidths are nearly identical in panel (b) and are presented as one point at the exact location of the CCT bandwidth.

16 Following Gelman et al. (2014), we do not include higher-order polynomial results in this paper.

An important diagnostic test of the regression discontinuity design assesses whether relevant covariates jump at the boundary. An identical spatial RD procedure is implemented but with these variables as dependent variables. Results are presented in Table 2 (page 28) for the CCT and IK bandwidths from columns (1)-(4) in Table 1. If covariates develop smoothly across the adjudication border, and identification is not threatened by other unobservables jumping at the boundary, the coefficient on the adjudication dummy should be insignificant in Table 2.

The results indicate that in most cases relevant covariates do not differ significantly at the discontinuity (and thus identification is not threatened by their omission). However, parcel area increases significantly in the IK sample (column (6)). That this result is not consistent across bandwidths, and indeed that no other covariates change in this manner, lessens concern about endogenous selection across the boundary or a problem with sample selection. (We include results using a per-unit-land dependent variable in Appendix, A.) Furthermore, that these particular covariates may vary across the boundary is not problematic if they are included in the regression specification; however, if relevant covariates seemingly differ across the boundary, there may be concern that other, unobserved characteristics also differ discontinuously. If these unobserved characteristics relate to land value, identification may be threatened.

To further asses the validity of our finding, a falsification test in space can be performed. To do so, we shrink the adjudicated region's area to 70% of its original, creating a new discontinuity in the interior. The new shape is anchored at the center of the original adjudicated area. We perform the same regression using this arbitrary boundary and find no clear effect, substantiating our interpretation of the identified effect as a result of the true adjudication boundary. Estimated coefficients are near zero with large standard errors. Results are in Table 3.

Table 3: Spatial RD - False Adjudication Boundary Test

	(1) Log LV	(2) Log LV	(3) Log LV	(4) Log LV
False Adjudication Dummy	-0.169	-0.0108	-0.0799	0.0513
	(0.182)	(0.143)	(0.226)	(0.174)
Boundary Distance	-0.0924*	0.0102	-0.0620	0.0478
	(0.0505)	(0.0474)	(0.166)	(0.139)
Distance*Adjudicated	0.161*	0.0179	0.00576	0.0103
	(0.0829)	(0.0671)	(0.0295)	(0.0252)
Distance^2			0.0472	-0.0850
			(0.250)	(0.196)
Distance^2*Adjudicated			-0.00279	-0.000423
			(0.0449)	(0.0351)
Constant	8.794***	-162.8***	8.821***	-161.2***
	(0.0946)	(47.95)	(0.137)	(44.56)
Observations	3,809	3,809	4,650	4,650
Bandwidth	IK(4.4km)	IK	IK (8.1km)	IK
Kernel	Uniform	Uniform	Uniform	Uniform
Covariates	None	Yes	None	Yes

Standard errors in parentheses and corrected for heteroscedasticity and spatial autocorrelation, and significance as follows: *** p<0.01, ** p<0.05, * p<0.1. Columns present resulting with linear/quadratic polynomials and IK bandwidths, alternating inclusion of covariates.

One additional test of boundary exogeneity is the McCrary test, which involves computing parcel density distributions on either side of the boundary (for more, see McCrary, 2008). A discontinuous jump in density at the boundary suggests that agents are sorting themselves around the boundary, or in our case that the boundary was drawn to exclude certain parcels or parcels were subdivided in response to adjudication. A McCrary test at 1-kilometer bandwidth indicates no spatial sorting or endogeneity (see Appendix, B) in the full sample.

Table 4 below presents results for the northwestern and southeastern segments of the adjudication boundary to assess whether the effect identified in Table 1 is spatially heterogeneous or being driven by one particular area of the Mojave groundwater basin. These segments correspond to management subareas within the adjudicated area that restrict trading spatially (a right cannot be traded outside of its subarea, so exchange prices vary across subareas). Estimation at the two subarea boundaries necessarily makes use of fewer observations.

Table 4: Assessed Values – Segment Effects

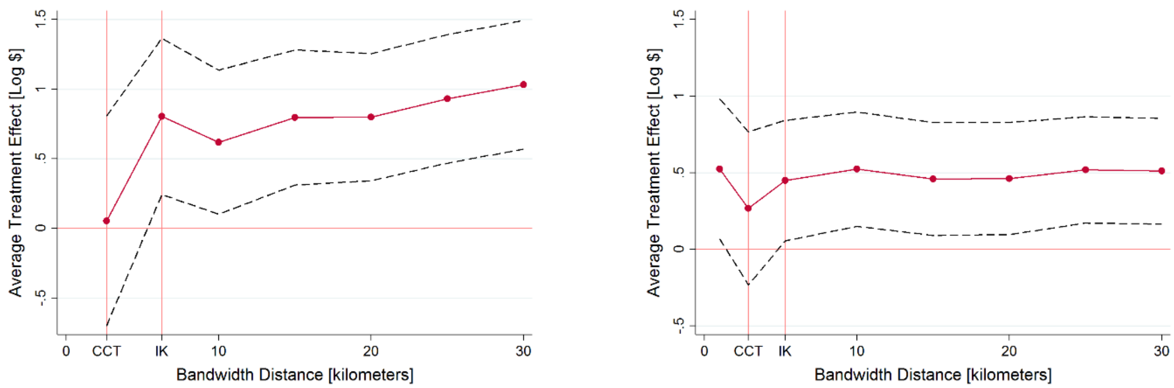
	Reference	Southeast (Este)		Northwest (Centro)	
	(1)	(2)	(3)	(4)	(5)
	Log LV	Log LV	Log LV	Log LV	Log LV
Adjudication Dummy	0.423**	0.384	0.858***	0.399	0.449**
	(0.202)	(0.467)	(0.324)	(0.254)	(0.201)
Boundary Distance	-0.276**	0.000034	-0.72***	0.0131	-0.0840
	(0.124)	(0.000137)	(0.102)	(0.0810)	(0.079)
Distance*Adjudicated	0.507***	-0.000187	1.07***	0.00960	0.108
	(0.141)	(0.000177)	(0.114)	(0.103)	(0.0979)
Observations	4,005	1,751	1,751	2,646	2,646
Bandwidth	IK	IK(6.3km)	IK	IK(5.3km)	IK
Kernel	Uniform	Uniform	Uniform	Uniform	Uniform
Covariates	Yes	None	Yes	None	Yes

Standard errors in parentheses and corrected for heteroscedasticity and spatial autocorrelation, and significance as follows: *** p<0.01, ** p<0.05, * p<0.1. Columns (2)/(3) present results for the Este Subarea and (4)/(5) for the Centro Subarea for IK bandwidths, alternating inclusion of covariates.

Column (1) reproduces for reference the result from the pooled sample using its own optimal IK bandwidth, which suggests about a 40% increase in land value at the boundary. Columns (2) and (3) correspond to the Este (southeast) Subarea, while (4) and (5) present results for the Centro (northwest) Subarea. In both segments the estimated RD effect is positive and significant when covariate controls are included. The point estimate in the southeast segment changes considerably when covariate controls are introduced, albeit in a way that accentuates the difference at the boundary. However, more insight is gained by plotting the treatment effects by bandwidth chosen, as in Figure 6 below. While the effect in the northwest (panel (b)) is, with one exception, consistent across bandwidths and in line with estimates from the pooled sample, the effect in the southeast segment is far less reliable. It increases with the bandwidth size and dissipates completely for the smallest bandwidth available, that suggested by the CCT algorithm.

Taken together, these results suggest an uncertain effect of adjudication on land value at the boundary of the Este Subarea.

Figure 6: ATE Estimates by Bandwidth – Southeast and Northwest Segments



(a) Southeast (Este) **(b) Northwest (Centro)**

Caption: Average Treatment Effect coefficients from regression discontinuity plotted against bandwidth chosen, including covariate controls. Vertical lines correspond to CCT and IK bandwidths, and 95% confidence intervals are shown in dashes.

This difference deserves attention. Two potential explanations exist: One boundary segment may contain a section of the aquifer with relatively low hydraulic conductivity across the boundary (so the returns to groundwater management may be more easily appropriable by users on the interior), or the volumetric rights allocated through the adjudication process may be more valuable in one subarea. Although both segments have relatively low hydraulic conductivity across the boundary, they are comparable with one another.[17] A more likely explanation is a difference in the capitalized value of permits. The Centro subarea contains a developing urban area, Barstow, California. Urban areas require guaranteed water access in perpetuity to fuel development; prior to adjudication, development was restricted because groundwater rights did not exist, but the definition of tradable property rights to the resource

17 Personal communication with Senior Hydrologist, Mojave Water Agency. 8 February 2017.

allows developers and water utilities to acquire rights to groundwater in perpetuity.[18] In doing so, developers bid up the price of groundwater pumping permits, increasing the present value of firms holding rights. This demand, or expectations of this future demand, may drive up the value of pumping rights; indeed; the sale price of a pumping right is substantially higher in the Centro subarea than it is the Este (Donohew, 2005).

VI. Discussion

Our results document a strong positive effect of adjudication that is robust to several different bandwidth choices and the inclusion of a set of covariates related to land value. Indeed, results from Table 1, indicate that the average effect of groundwater adjudication is to increase vacant and agricultural land values by 40 to 50%. Theory suggests that this effect is positive where the capitalized value of groundwater pumping permits exceeds the agricultural rent premium enjoyed by free riders outside the adjudicated area. We find evidence that this is the case, although we cannot isolate the effect of free riding. Furthermore, water scarcity is a major restriction on development and many municipalities, water utilities, and counties adopt resolutions that require proof of water access before land can be developed. San Bernardino County has such a requirement. Groundwater adjudication provides developers with certainty over access to groundwater resources in perpetuity, and their demand, or expectations of their future demand, drives up capitalized permit values that are included in land value (see Section IV).

The estimated magnitudes of these effects are quite large. An increase in land value of 40% may equate to tens of thousands of dollars, or more. These estimates must be placed in

18 Indeed, municipalities in our study area have been growing rapidly over the past few decades and have aggressively acquired water rights to fuel this growth.

context. In the Mojave, water is the major constraint on both agriculture and urban development, not land. As a result, institutional changes to the use of groundwater (the primary source of water in the region) can generate a great deal of economic value, which is reflected in groundwater rights. When these rights are included in land values, a substantial effect on the reported value of that land will result. Consider that some groundwater pumping right bundles have traded for millions of dollars (compared to an average land sale price of between $10,000-20,000). Furthermore, evidence suggests that the Mojave aquifer would have suffered considerable additional drawdown, potentially rendering it unfit for most uses, in the absence of intervention. By the 1980s, it is was estimated that two-fifths of the aquifer's total storage capacity had already been extracted, and water tables fell 50-100 feet in the decades preceding adjudication (Donohew, 2005).

Our analysis of separate segments of the adjudication boundary indicates that the Centro Subarea of our study area exhibits a more reliably positive treatment effect than the Este Subarea. This may be due to anticipated urban growth within the subarea, which increases expected future permit values and is reflected in land values through the inclusion of groundwater rights values into assessed land value.[19] Indeed, urban areas in the sample region have been growing steadily since adjudication and have bought up groundwater pumping rights from marginal agricultural users to do so.

Our main results are corroborated by a falsification test in space, where we find no substantial evidence of land value discontinuities across an arbitrary boundary above the aquifer. Furthermore, these results are supported by anecdotal evidence from the study region. Cropping patterns have changed significantly since adjudication, as farmers have switched to higher-value

19 Note that this effect does not depend on a landowner's distance from an urban area because "paper" water can be traded over any distance, provided the buyer is within the same subarea of the adjudication.

yet more water-sensitive crops such as almonds and pistachios. On the other hand, the benefits of free ridership are also clear: local wisdom suggests that anyone interested in entering agricultural production in the basin should consider buying land outside the adjudicated area in order to avoid pumping restrictions. Municipalities have actually tried to avoid restrictions. The Phelan community services district in the southwestern corner of the study area recently drilled wells 50-100 feet outside the western boundary of the adjudication in order to access groundwater that is hydrologically connected to the main Mojave aquifer and thereby circumvent restrictions.[20] Finally, the narrative of adjudication negotiations sheds light: a small group of agricultural holdouts known as the "Cardozo Group" challenged the initial agreement in court, alleging that their unconstrained groundwater pumping rights could not be altered without their consent. The California Supreme Court concurred and allowed them to maintain their original overlying rights to pump as much as needed in parallel with the new system adopted by cooperating users. Despite subsequent bargaining and even financial offers to encourage adoption by these holdouts, it was only after learning about the value of the rights being sold to municipal users that the recalcitrant users agreed to adopt restrictions in return for tradable pumping allocations.

VII. Conclusion

The results presented here document a positive, statistically significant, and economically meaningful effect of groundwater adjudication on agricultural and vacant land values. In some cases, the average treatment effect implies a 50% increase in land value. This large effect reflects the tight restriction that groundwater places on both urban and agricultural development in the Mojave. Furthermore, the results indicate that gains from trade are substantial when demand

20 Personal communication with Senior Hydrologist, Mojave Water Agency. 8 February 2017

growth is present and a market approach to reallocation is adopted: markets allow efficient agricultural producers to continue growing crops despite pumping restrictions and urban areas to expand more rapidly and with more certainty, which results in high permit prices that are capitalized into land value.

This work contributes to the literature on common-pool resource management by documenting the returns to collective action to restrict open-access extraction rates. While recent studies have either addressed the adaptation of users to new institutions (Smith et al., 2017) or the economic returns to less stringent management institutions (Edwards, 2016), this investigation is the first to assess the impact of tradable property rights to groundwater on land value using parcel-level data. This work also fits into a larger literature that documents the margins along which economic gains accrue to common-pool resource users when management institutions are adopted, in this case in the value of a complementary production input. In addition, the econometric results suggestively document that when urban areas seek to solve the common-pool problem in order to grow in water-constrained environments, side payments to oftentimes recalcitrant agricultural users can take the form of grandfathered water rights.

In addition, insights gained from this project will help to streamline the implementation of California's Sustainable Groundwater Management Act of 2014. Numerous stakeholder organizations are currently embroiled in negotiations over how to manage groundwater aquifers to avoid "undesirable outcomes," as defined in this legislation. Historically, collective responses to groundwater overdraft have remained elusive in California due to high transaction costs in bargaining over management institutions (Ayres et al., 2017), but recent attempts have been made to simplify the adjudication process to reduce these costs.[21] Nonetheless, reaching

21 For example, California Assembly Bill 1390 (2015-16).

agreement on pumping restrictions remains very difficult. This analysis demonstrates that private benefits accrue to landowners who collectively adopt pumping restrictions to address over-extraction. Users and regulators alike may hope that a promise of appropriable gains in resource values can help ease negotiating tensions and support sustainable groundwater management.

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IX. Results Appendix

A. *Unit Dependent Variable ($/Acre)*

Table 5 presents regression discontinuity results for dollars per acre. Although point estimates are reliably positive and of plausible magnitudes, statistical significance is inconsistent.

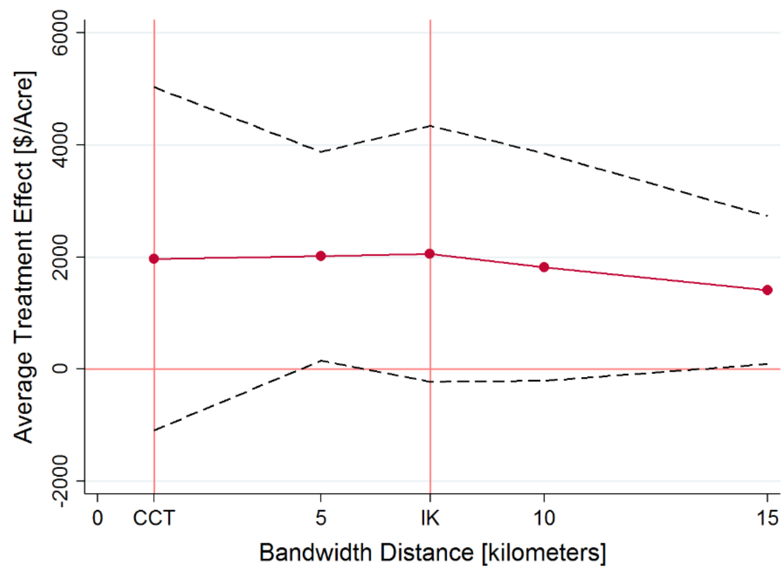
Table 5: Spatial RD Results - $/Acre

	(1) Log LV	(2) Log LV	(3) Log LV	(4) Log LV	(5) Log LV	(6) Log LV	(7) Log LV	(8) Log LV
Adjudication Dummy	1,483	1,970	1,155	2,059*	1,872	2,414	109.7	2,118**
	(1,607)	(1,561)	(808.8)	(1,165)	(1,726)	(1,648)	(768.9)	(996.4)
Boundary Distance	492.3	-376.8	164.2***	-432.5*	950.8	-765.0	250.7*	-1,320***
	(430.3)	(437.4)	(54.40)	(233.4)	(694.6)	(663.3)	(134.3)	(478.0)
Distance*Adjudicated	-2,597	-1,276	-139.6	282.5*	377.7	-284.6	16.72	-82.90**
	(1,579)	(1,211)	(126.6)	(165.4)	(284.5)	(258.3)	(12.48)	(35.61)
Distance^2					-5,400**	-2,750	285.5	1,406**
					(2,378)	(1,812)	(432.3)	(583.5)
Distance^2*Adjudicated					1,489*	1,755**	-59.13	48.28
					(863.5)	(812.2)	(41.40)	(34.76)
Covariate Controls								
Parcel Area		-6.741**		-12.08***		-7.283***		-10.76***
		(3.247)		(3.261)		(2.240)		(2.440)
Base Year		-0.159		0.219**		0.0240		0.0632
		(0.184)		(0.107)		(0.118)		(0.110)
Distance to Urban Center		-12.36		-256.3*		-15.97		-202.5**
		(115.7)		(143.8)		(47.40)		(99.04)
Recharge Distance		30,520		21,709		14,399		74,857*
		(29,983)		(15,489)		(11,986)		(43,131)
Average Slope		39.64		203.0		-14.85		136.6
		(40.91)		(282.5)		(35.64)		(209.3)
Latitude		-4,163		-1,477		-3,912**		-2,968**
		(2,588)		(1,054)		(1,936)		(1,183)
Longitude		-5,442***		-7,292***		-5,072***		-9,453***
		(1,613)		(2,440)		(1,111)		(2,534)
Constant	1,813***	-4.9e5***	1,763***	-7.9e5***	1,889***	-4.6e5***	1,814***	-1.0e6***
	(469.2)	(123,832)	(295.2)	(271,615)	(472.8)	(74,248)	(326.0)	(287,211)
Observations	763	763	5,248	5,248	1,608	1,608	7,690	7,690
Bandwidth	CCT(1.3km)	CCT	IK (7.4km)	IK	CCT(2.3km)	CCT	IK(10.8km)	IK
Kernel	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform	Uniform
Covariates	None	Yes	None	Yes	None	Yes	None	Yes

Standard errors in parentheses and corrected for heteroscedasticity and spatial autocorrelation, and significance as follows: *** p<0.01, ** p<0.05, * p<0.1. Columns present results for linear and quadratic polynomials using CCT and IK bandwidths, alternating inclusion of covariates.

Figure 5 below presents average treatment effect estimates by bandwidth. Point estimates hover between $1,500 and $2,000 per acre, sometimes achieving statistical significance at the 5% level and regularly at the 10% level.

Figure 5: ATE Estimates by Bandwidth - $/Acre, All Segments

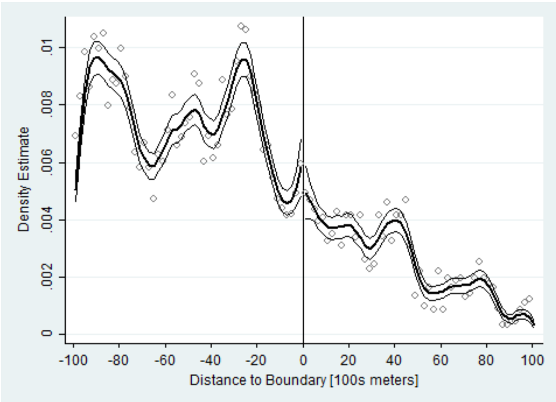


Caption: Average Treatment Effect coefficients from regression discontinuity plotted against bandwidth chosen, including covariate controls. Vertical lines correspond to CCT and IK bandwidths, and 95% confidence intervals are shown in dashes.

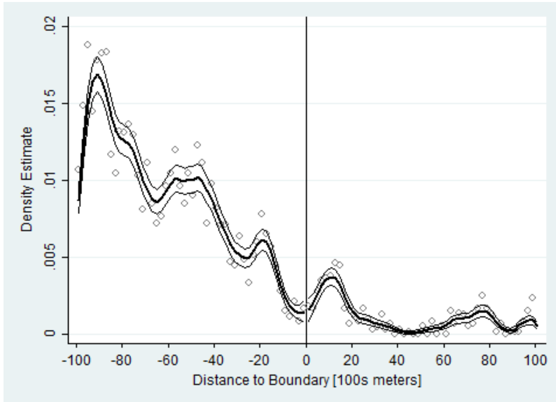
B. McCrary Tests

Presented below in Figure 6, plots (a)-(d), are McCrary test outputs at 10 kilometers (adjudicated parcels are on the left). Density estimates are not statistically different across the border for all segments except in the Este Subarea. This imbalance results from topography as well as patterns of government land ownership and requires that we omit this subarea from the regression discontinuity analysis.

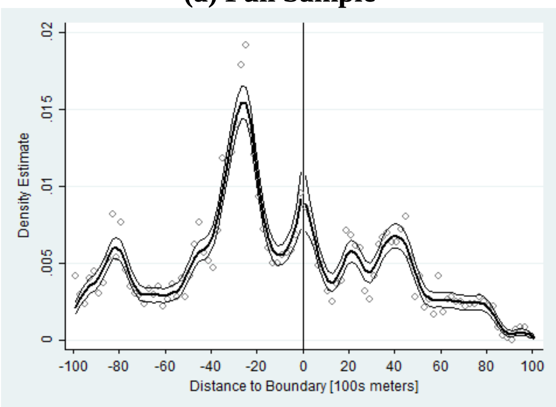
Figure 6: McCrary Test Results



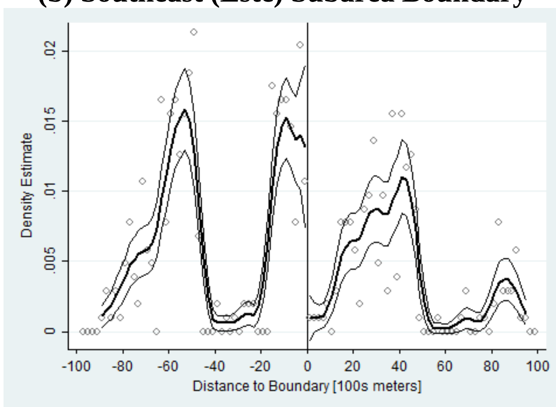
(a) Full Sample



(b) Southeast (Este) Subarea Boundary



(c) Southeast (Este) Subarea Boundary



(d) Southeast (Este) Subarea Boundary